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TORNADO COMPOSITE CHARTS

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ABSTRACT

Composite charts of height (or sea level pressure), temperature, and dew point were prepared for the surface, 850-, 700-, and 500-mb. levels for tornado occurrences in 6 different areas in the United States. Cases selected for inclusion in these composite charts were mostly based upon the occurrence of 3 or more tornadoes within any one of the 6 areas during a 12-hour period. The number of cases ranged from 17 to 66 in any one area with a total of 229 cases. These charts present a mean picture of synoptic conditions from 0 to 12 hours before the outbreak of tornadoes for each of the 6 areas. In spite of seasonal and geographical differences in data, the similarity of patterns is striking.

1. INTRODUCTION

The preparation of composite charts for selected weather situations provides one means for identifying larger-scale features which are common to these situations. Also, composite charts clearly depict anomalies or departures from normal. The primary purpose of this study was to determine the common characteristics of tornado situations with varying geographic locations as well as anomalies. It was expected that such a study would provide some basis for further research regarding the larger-scale weather features of the environment in which tornadoes develop. It was originally planned that these data would be analyzed in considerable detail and the findings discussed in the paper. However, time has not yet permitted such an analysis, and so it was decided to make the analyzed charts, and some tentative conclusions, more widely available.

2. SELECTION AND COMPILATION OF DATA

The work reported upon here represents an extension of a project initiated by the Short Range Forecasting Development Section of the Weather Bureau, the results of which were given limited distribution in manuscript form [1]. The present study includes composite charts for the continental United States of height (or sea level pressure), temperature, and dew point for the surface, 850-, 700-,

FIGURE 1.—Map showing areas in which tornadoes were reported for compilation of data for composite charts. Upper number shows number of cases, lower, number of tornadoes.

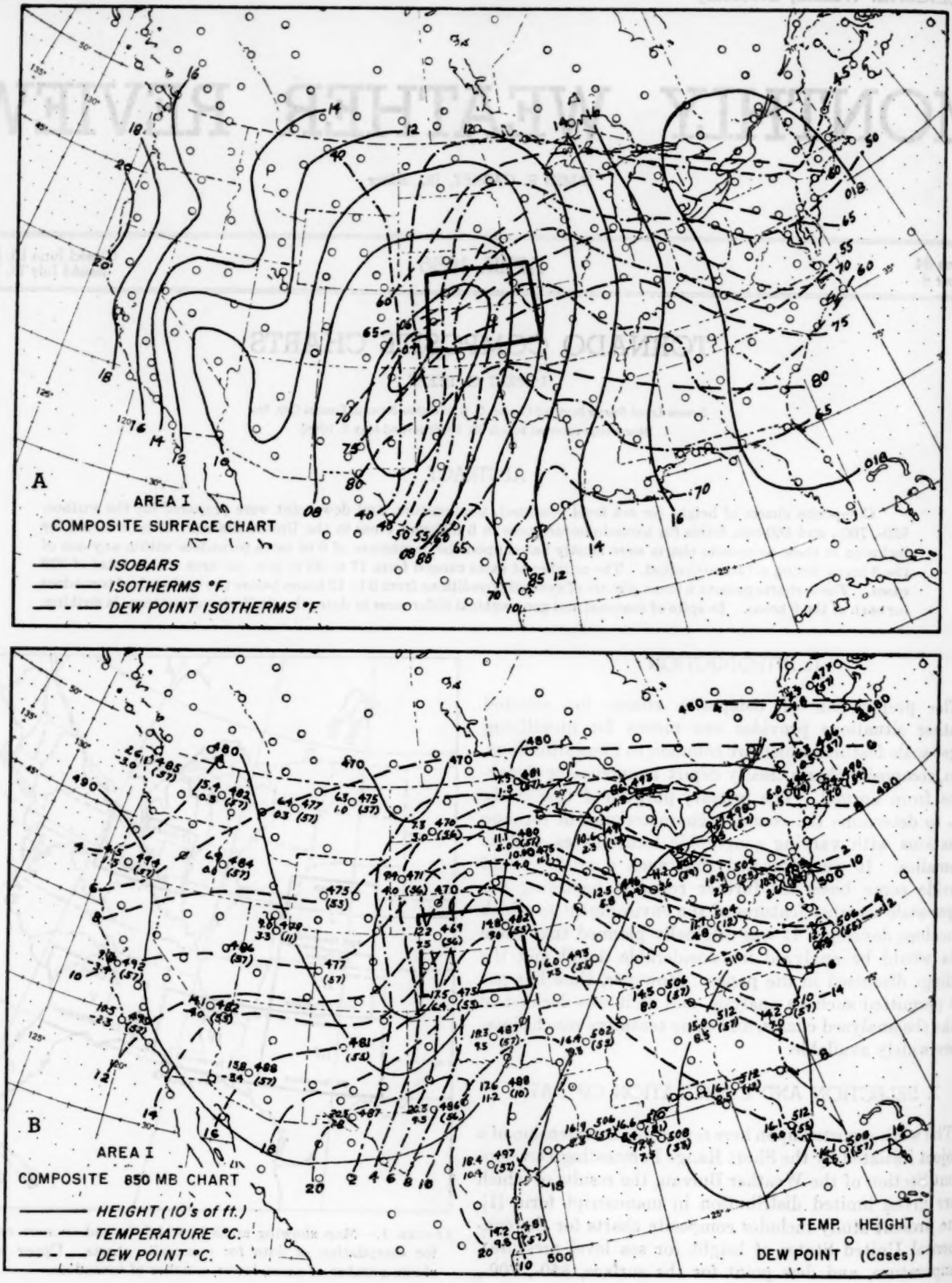
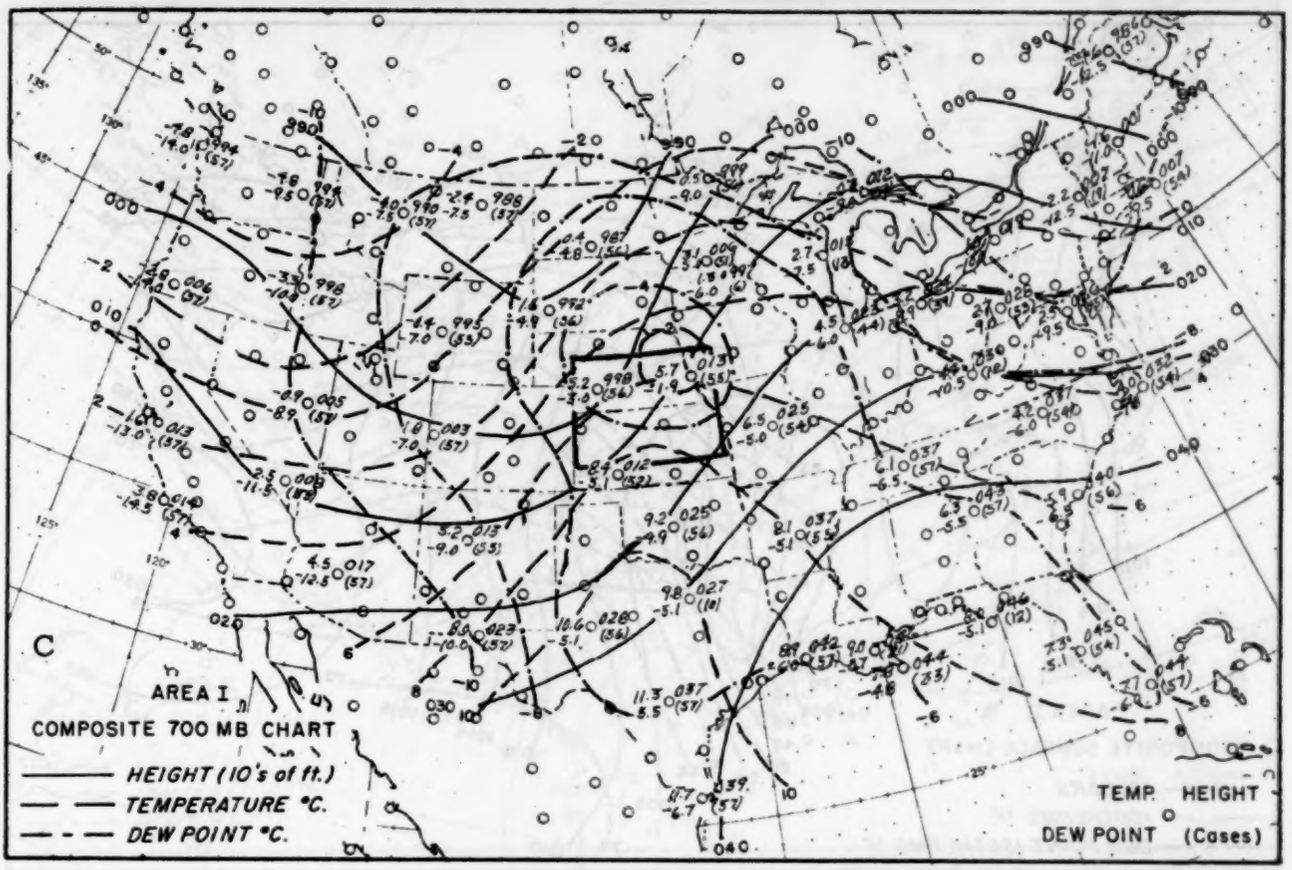


FIGURE 2.—Composite maps based upon data from 57 different tornado situations (366 tornadoes) that occurred in area I (outlined) from March through June, 1945 through 1953. (A) Surface, (B) 850 mb., (C) 700 mb., (D) 500 mb.



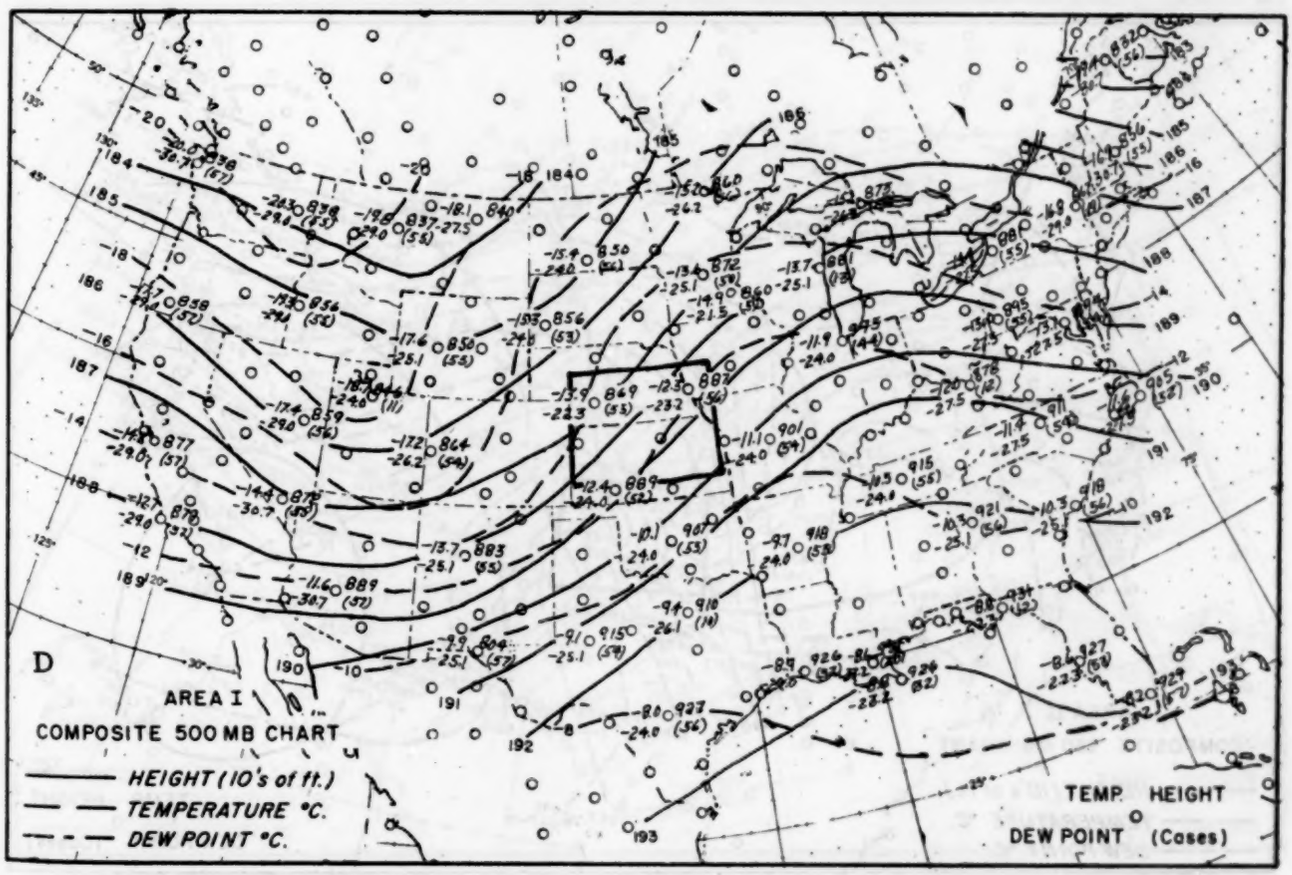


FIGURE 2—Continued.

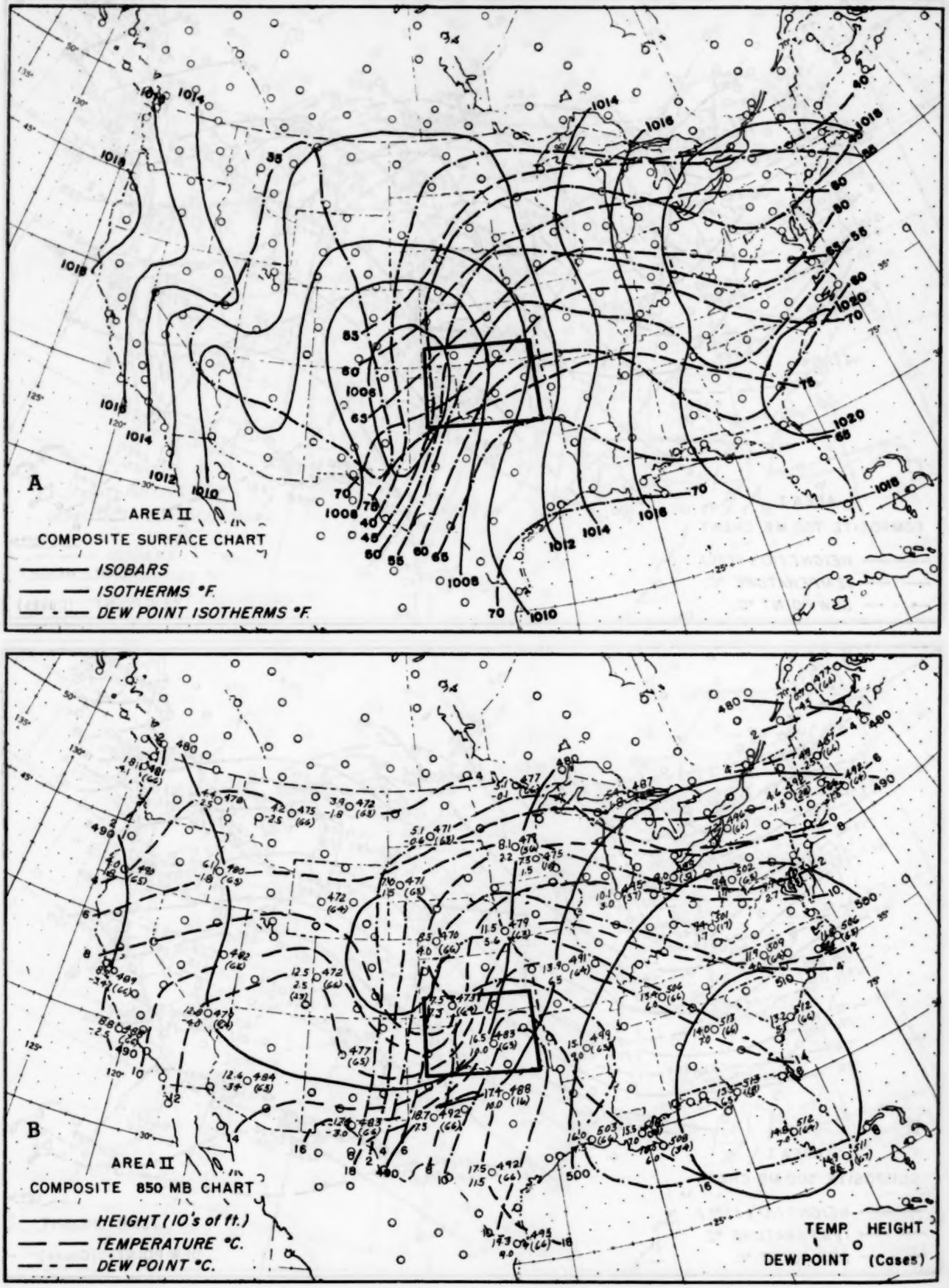
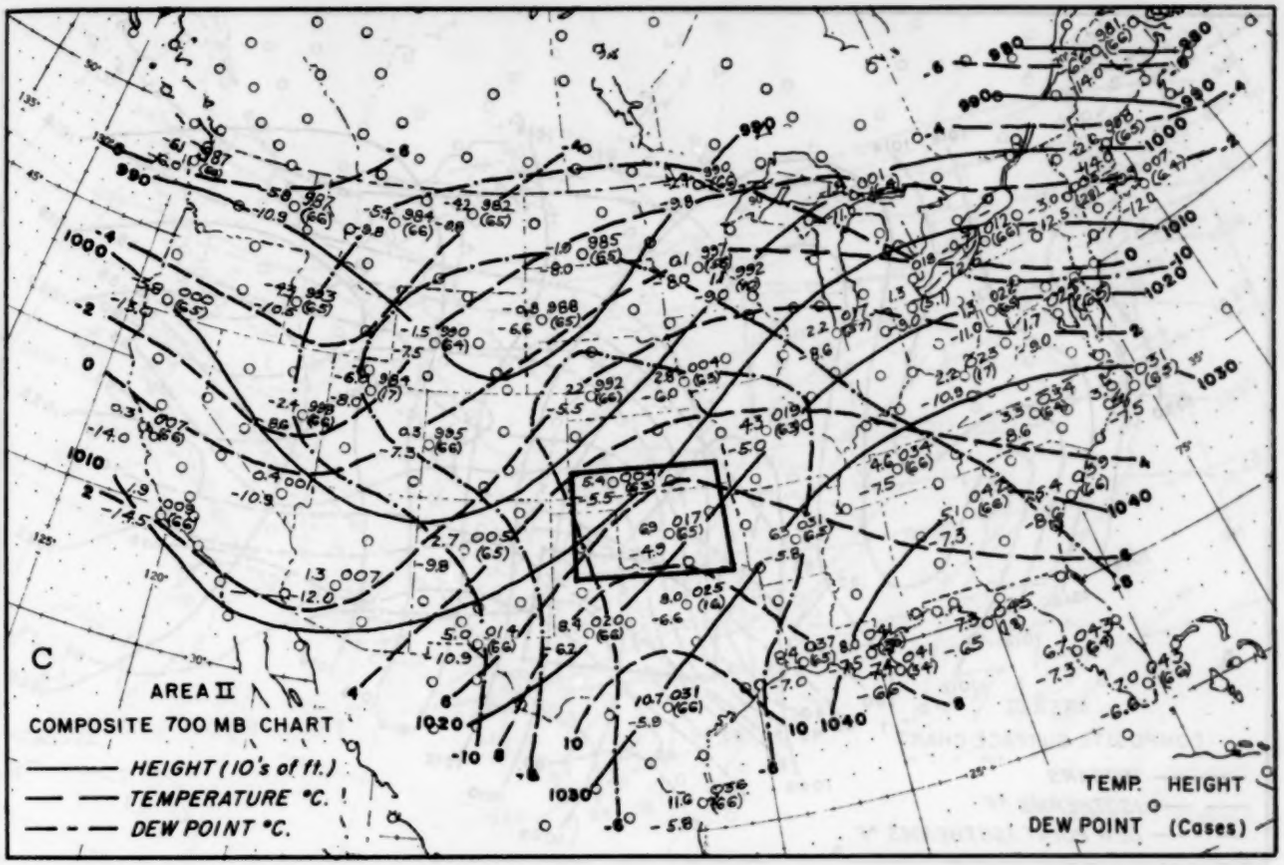
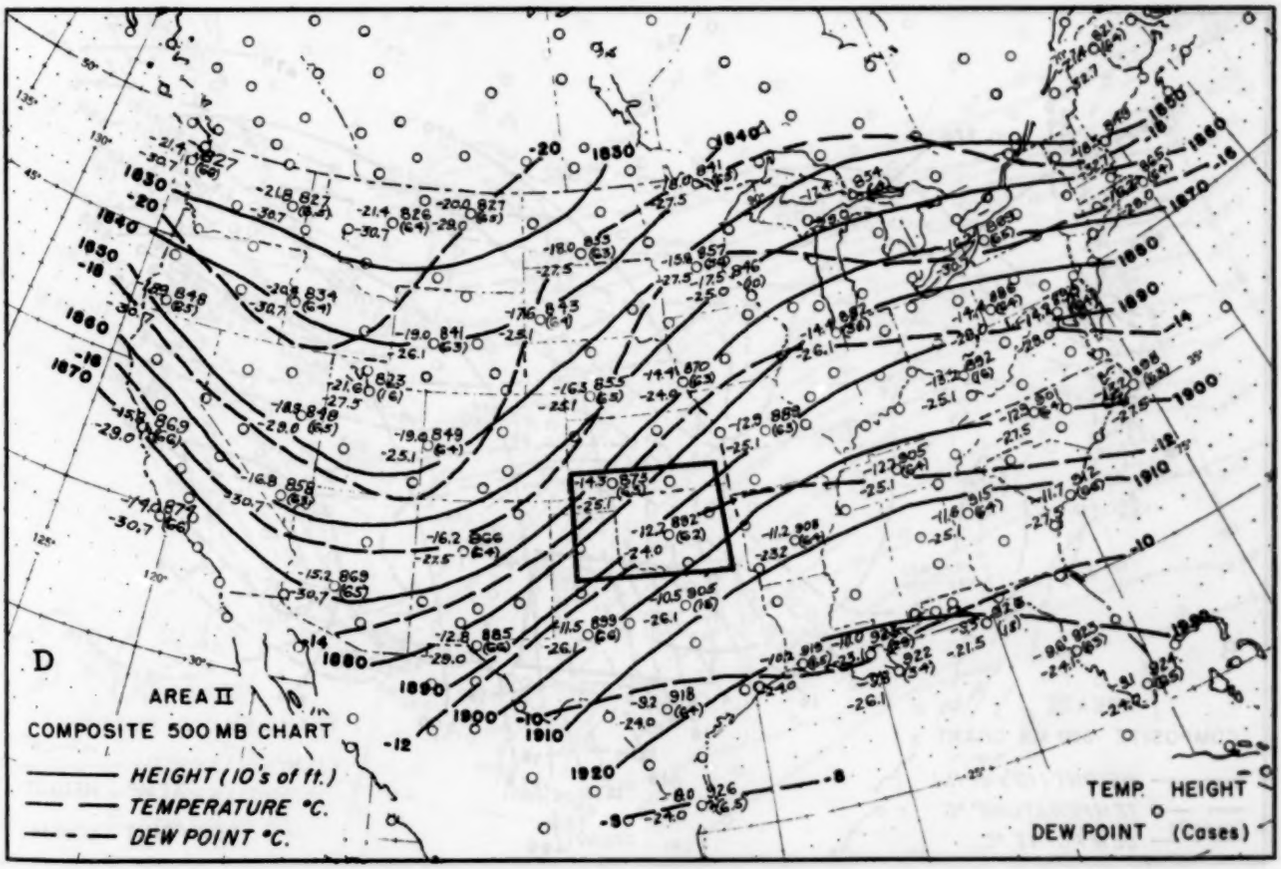


FIGURE 3.—Composite maps from 66 tornado situations (449 tornadoes) that occurred in area II from March through June 1945 through 1953. (A) Surface, (B) 850 mb., (C) 700 mb., (D) 500 mb.





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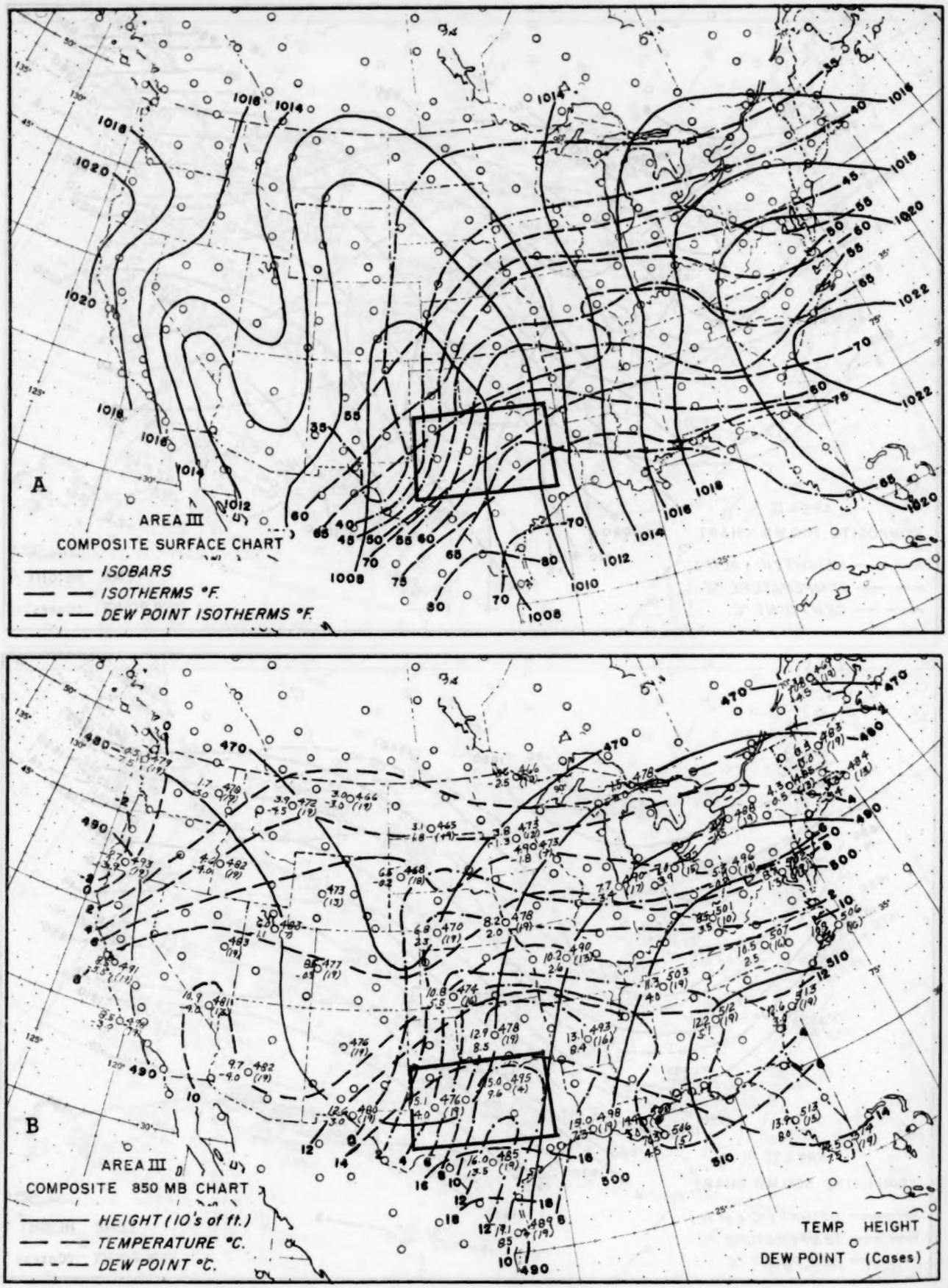
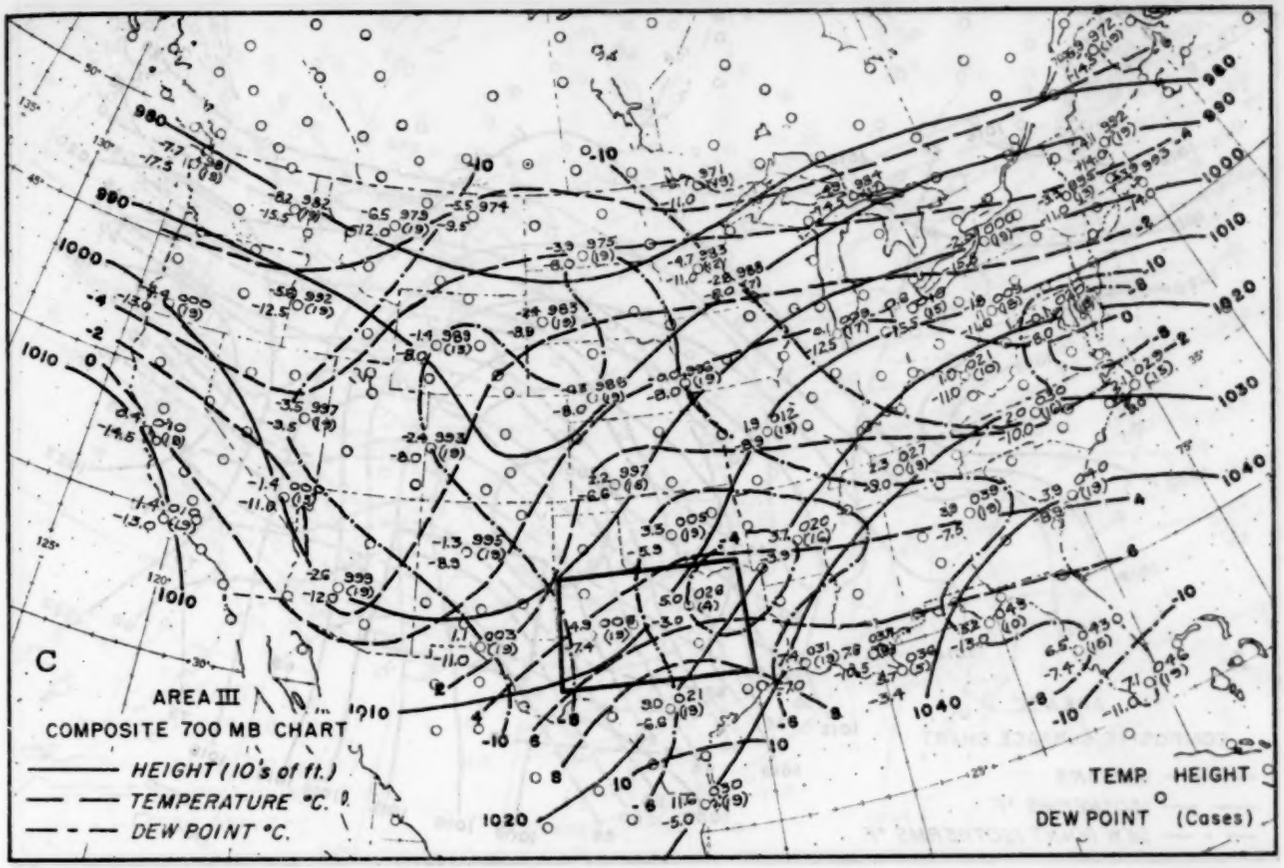
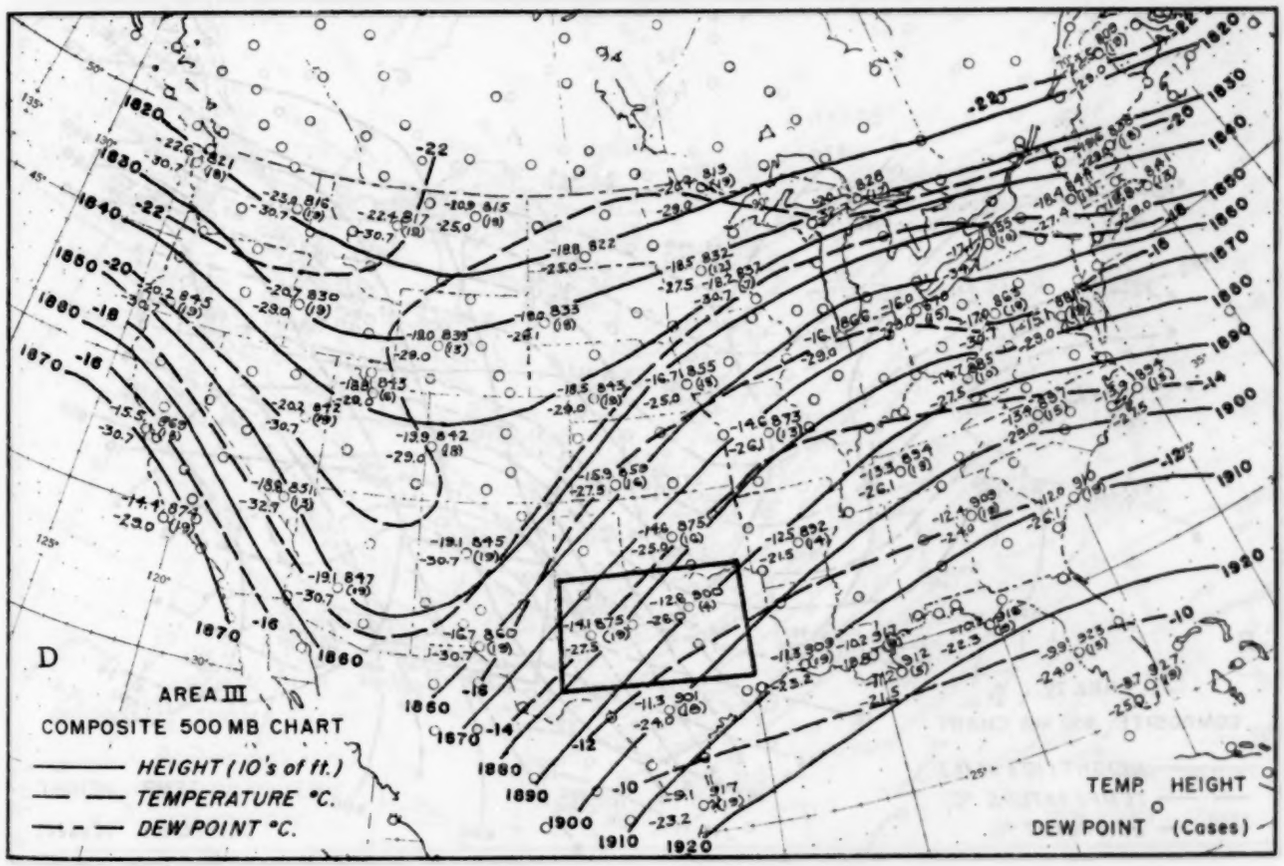


FIGURE 4.—Composite maps from 19 tornado situations (74 tornadoes) that occurred in area III from February through June 1945 through 1953. (A) Surface, (B) 850 mb., (C) 700 mb., (D) 500 mb.





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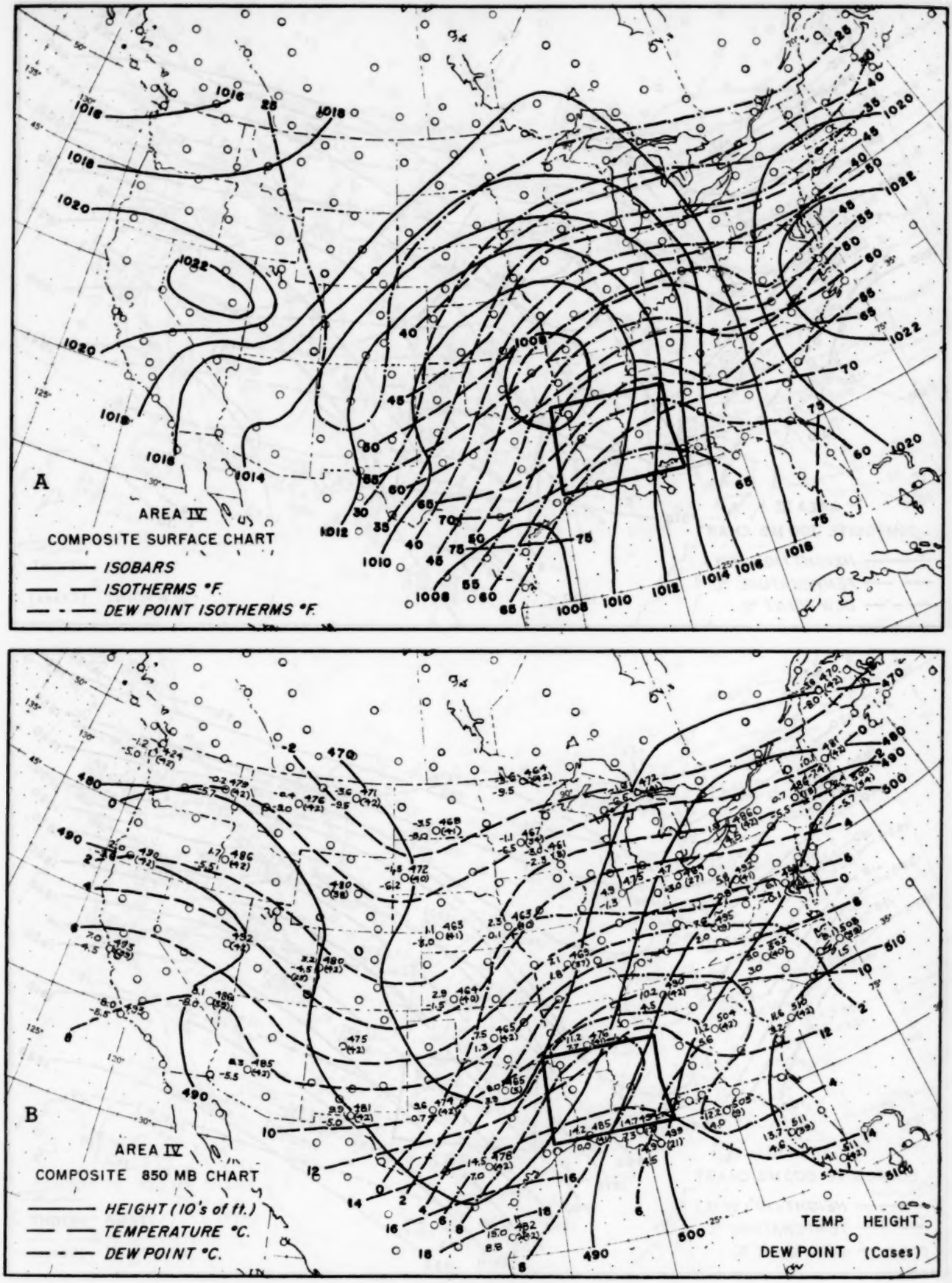
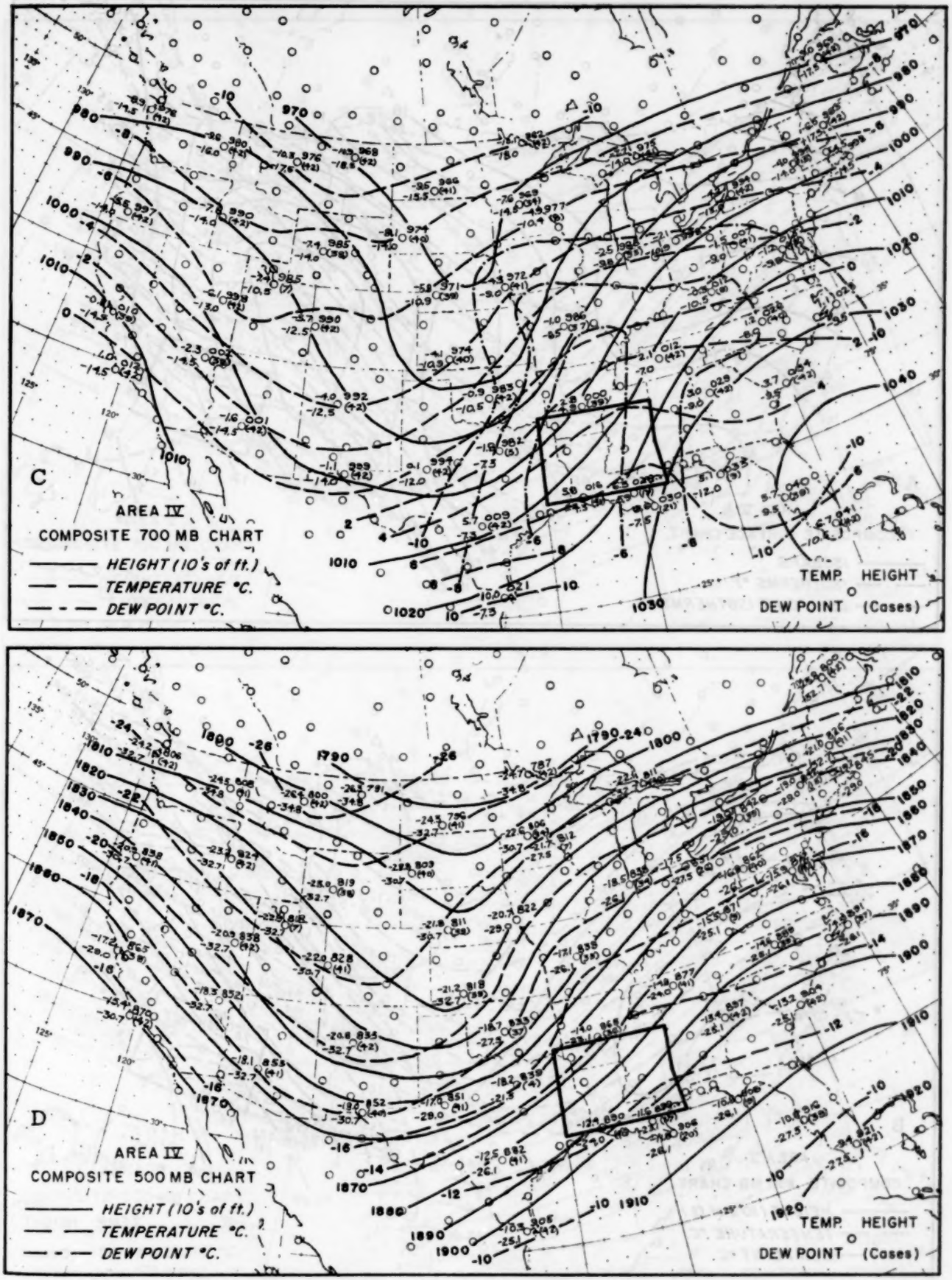


FIGURE 5.—Composite maps from 42 tornado situations (191 tornadoes) that occurred in area IV from January through May 1945 through 1953. (A) Surface, (B) 850 mb., (C) 700 mb., (D) 500 mb.



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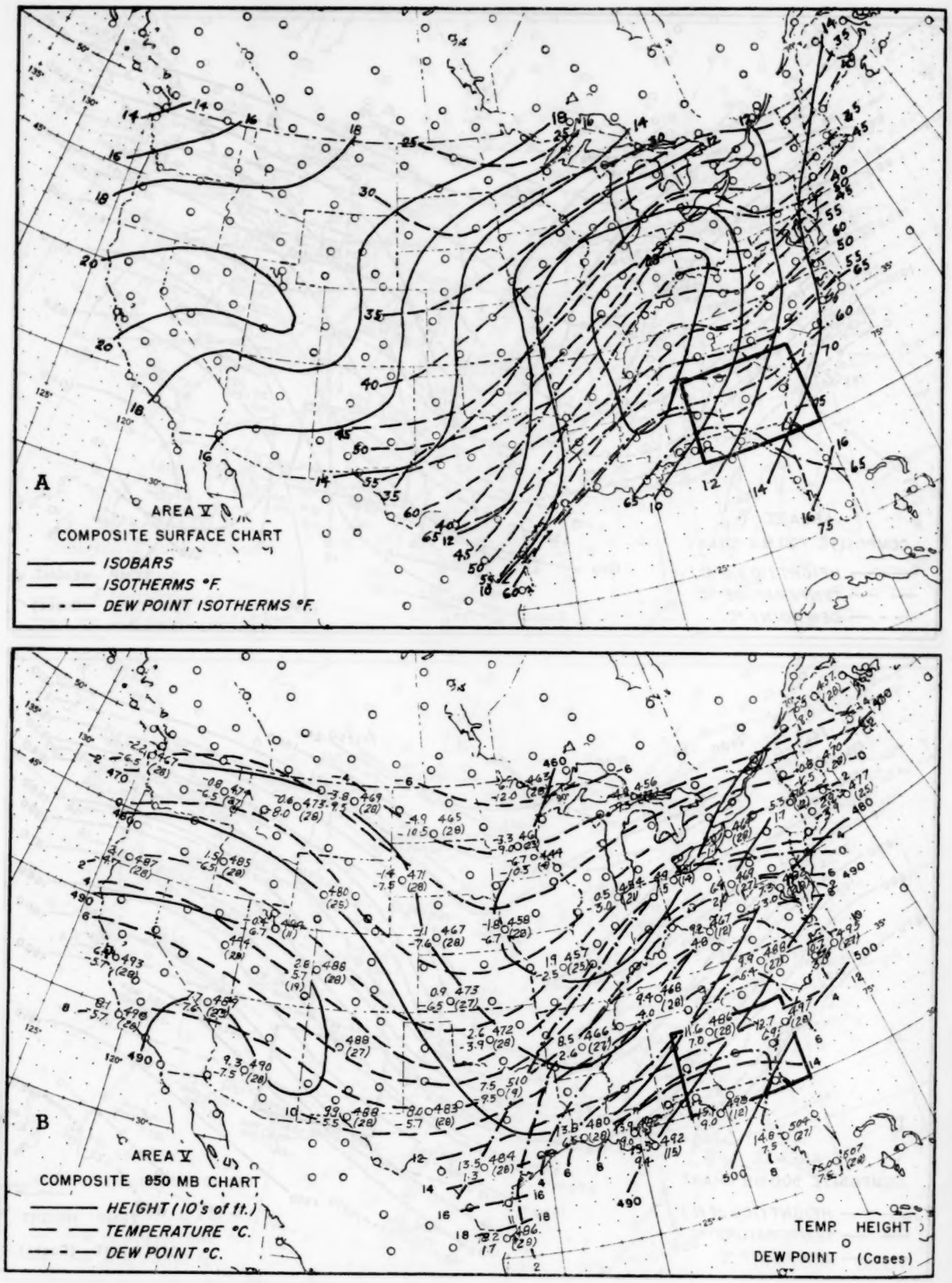
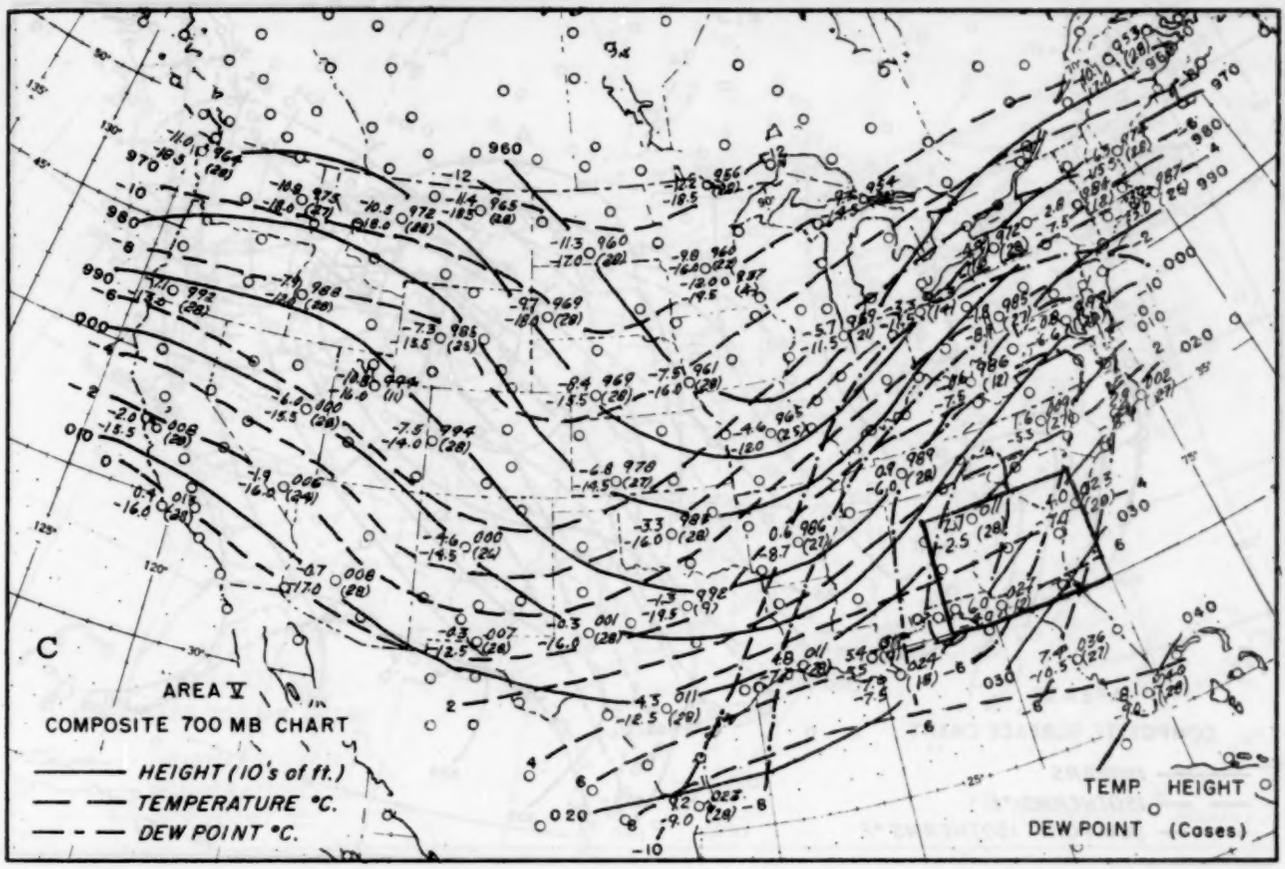
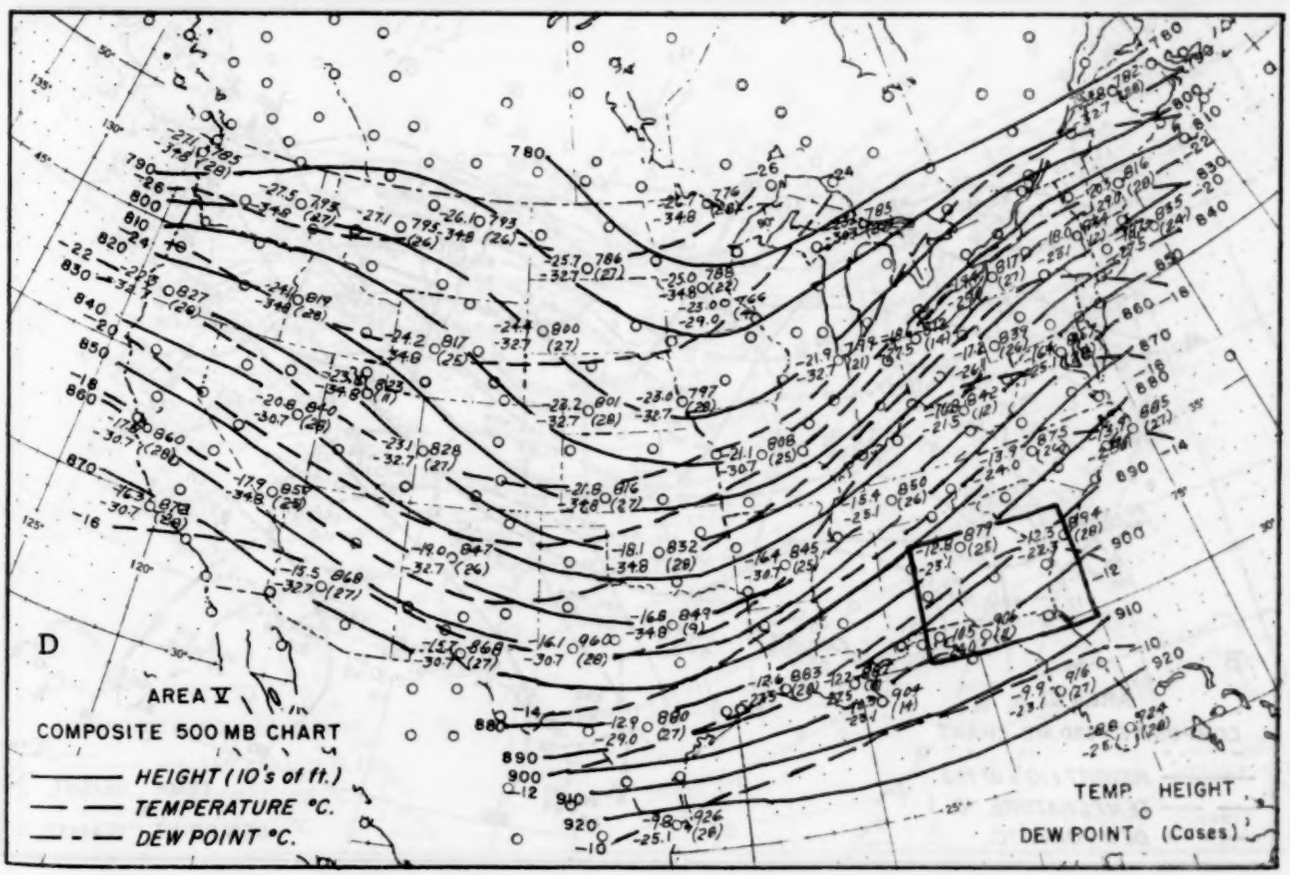


FIGURE 6.—Composite maps from 28 tornado situations (128 tornadoes) that occurred in area V from January through May 1945 through 1953. (A) Surface, (B) 850 mb., (C) 700 mb., (D) 500 mb.





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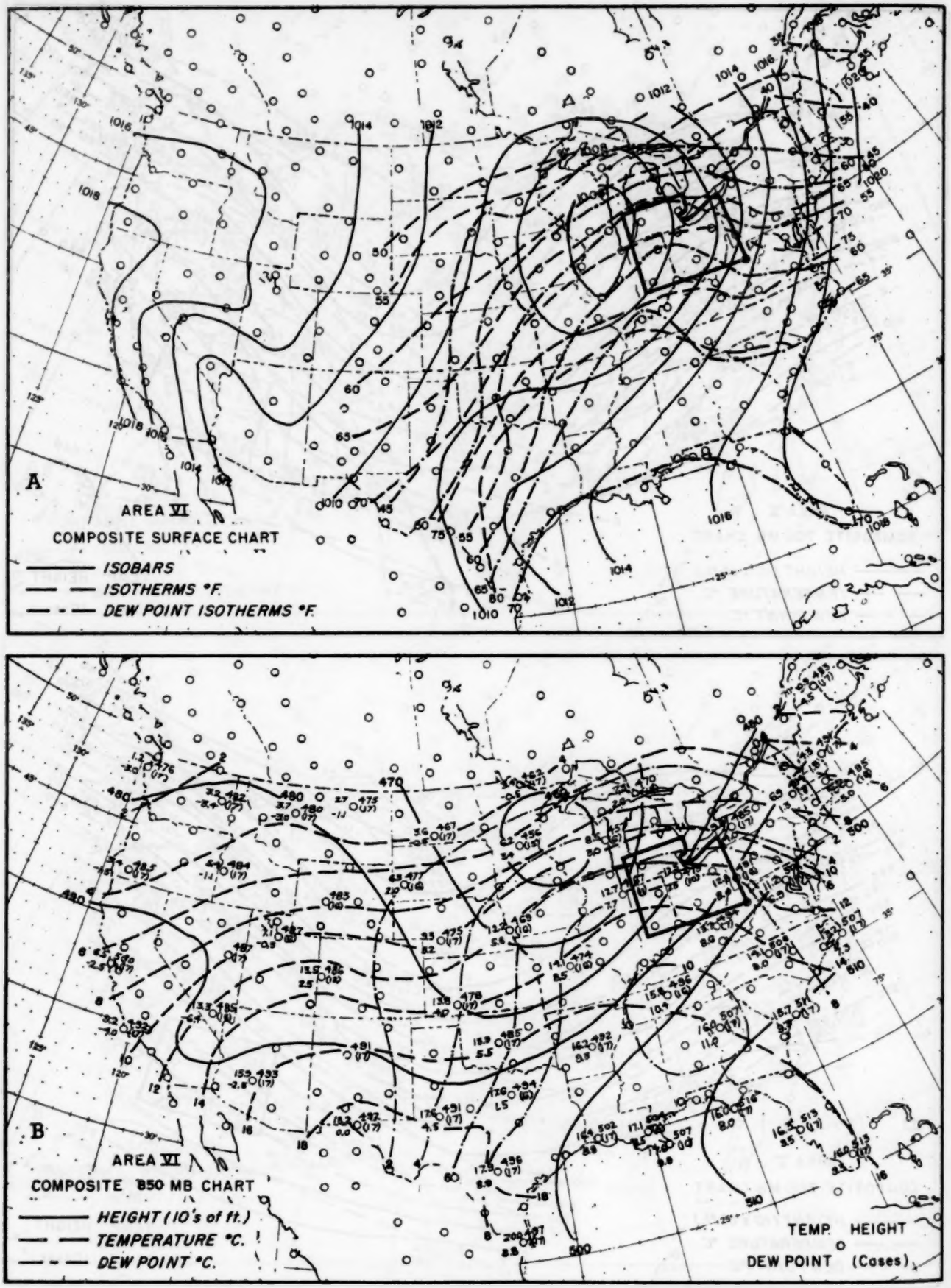
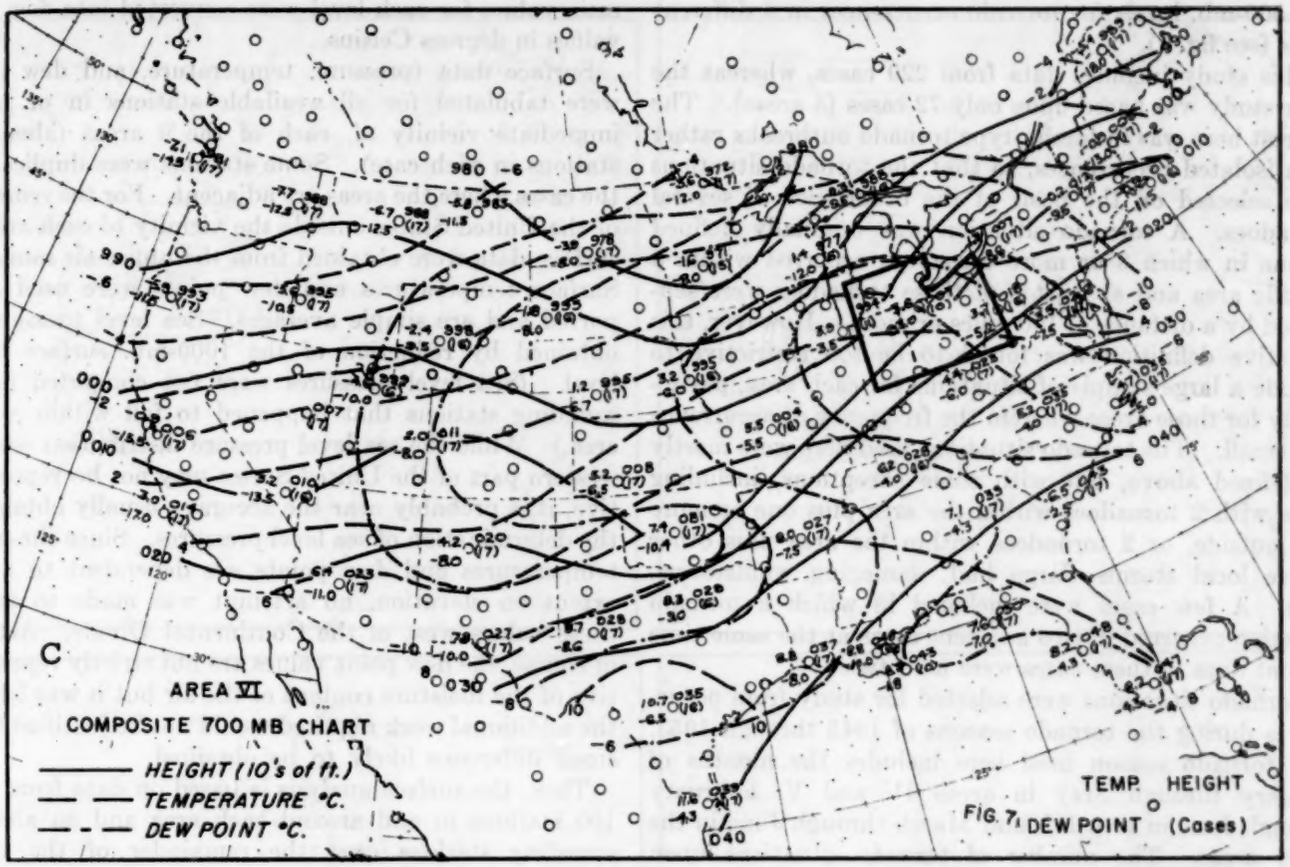


FIGURE 7.—Composite maps from 17 tornado situations (98 tornadoes) that occurred in area VI from March through June 1945 through 1953. (A) Surface, (B) 850 mb., (C) 700 mb., (D) 500 mb.



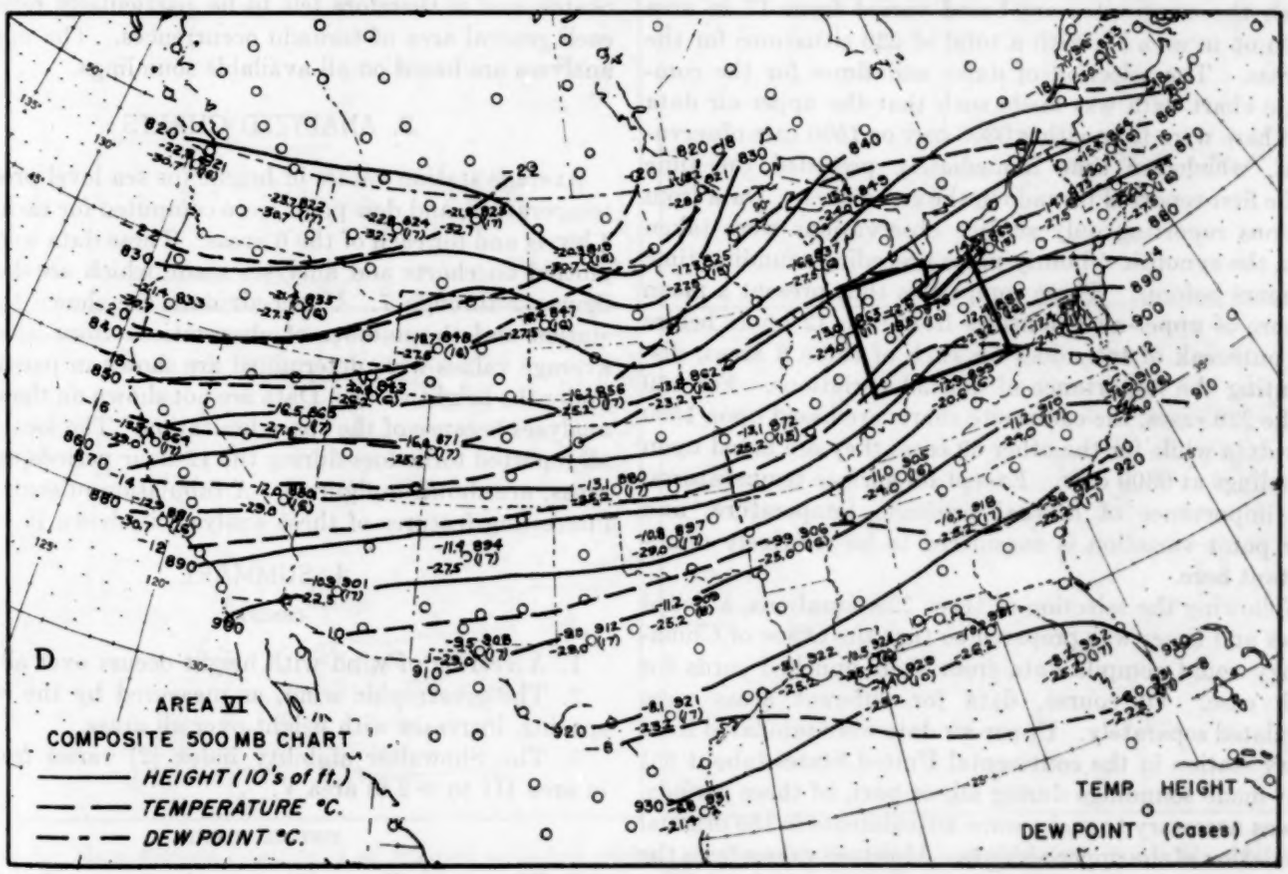


FIG. 7.

FIGURE 7—Continued.

and 500-mb. levels for tornado occurrences in 6 different areas (see fig. 1).

This study includes data from 229 cases, whereas the prior study was based upon only 72 cases (5 areas). The interest here was in family-type tornado outbreaks rather than isolated occurrences, so that the tornado situations were selected on the basis of the occurrence of several tornadoes. A tornado situation was originally defined as one in which 3 or more tornadoes occurred within a specific area and at least 2 of these tornadoes were separated by a distance of 100 miles or more. However, this objective definition was found to be too restrictive to include a large sample of situations for each area, particularly for those areas wherein the frequency of occurrence was small. The tornado situations used here were mostly as defined above, but with some exceptions, including cases with 2 tornadoes within the area plus one or more just outside, or 2 tornadoes within the area plus other severe local storms (large hail, damaging windstorms, etc.). A few cases were included in which a tornado situation occurred in two adjacent areas at the same time so that data in these cases were used twice.

Tornado situations were selected for study from occurrences during the tornado seasons of 1945 through 1953. The tornado season used here includes the months of January through May in areas IV and V, February through June in area III, and March through June in the other areas. The number of tornado situations upon which the composites are based varied from 17 in area VI to 66 in area II, with a total of 229 situations for the 6 areas. The selection of dates and times for the composite chart data was made such that the upper-air data used here were from either 0300 GMT or 1500 GMT observations, whichever time immediately preceded the time of the first reported tornado in the given area. Data from stations reporting only surface observations were taken from the synoptic 6-hourly maps preceding sounding time (3 hours before). These composites thus present a mean picture of upper-air conditions from 0 to 12 hours before the outbreak of tornadoes for each of these 6 areas, discounting the importance of diurnal variations. For 169 of the 229 cases, the composite charts are based upon 1500 GMT data while for the other 60 cases they are based upon soundings at 0300 GMT. Except for surface temperatures, the importance of diurnal pressure, temperature, and dew point variation is considered to be relatively unimportant here.

Following the selection of these 229 situations, a list of dates and times was prepared so that the Office of Climatology could compile data from their punched cards for each case. Of course, data for different areas were tabulated separately. Upper-air data were tabulated from every station in the continental United States (about 55) that made soundings during all, or part, of these periods. It was necessary to make some adjustments in the original tabulation of the upper-air data. Moisture values from the soundings were in terms of mixing ratio. These mixing ratio values for each level were converted into dew point values in degrees Celsius.

Surface data (pressure, temperature, and dew point) were tabulated for all available stations in or in the immediate vicinity of, each of the 6 areas (about 100 stations in each case). Some stations were duplicates in the cases where the areas are adjacent. For the remainder of the United States outside the vicinity of each area the surface data were obtained from the upper-air soundings. Surface temperatures and dew points were used as reported and are simple averages. Sea level pressure was obtained by reduction of the 1000-mb. surface to sea level. (Sea level pressures were not computed for the sounding stations that happened to fall within a given area.) While the sea level pressure distribution over the western part of the United States may not be representative, it is probably near the accuracy usually obtained in the determination of sea level pressures. Since the surface temperatures and dew points are dependent to a large extent on elevation, no attempt was made to analyze these values west of the Continental Divide. Actually, of course, the dew point values are not strictly representative of the moisture content of the air but it was felt that the additional work required would not be justified by the small difference likely to be obtained.

Thus, the surface analysis is based on data from about 100 stations in and around each area and on about 50 sounding stations over the remainder of the United States, and is therefore felt to be particularly reliable in each general area of tornado occurrences. The upper-air analyses are based on all available soundings.

3. ANALYZED CHARTS

Average station values of height (or sea level pressure), temperature, and dew point were computed for each of the 4 levels and for each of the 6 areas. These data were then plotted on charts and analyses made which are shown in figures 2 through 7. Upper-air data are shown for each station and the number of observations from which the average values were determined are shown in parentheses under the height value. Data are not shown on the surface analyses because of the space limitation. The locations of all reported tornadoes during the 12-hour periods used, by areas, are shown in figure 8. A tabulation of some of the interesting features of these analyses is shown in table 1.

4. SUMMARY

GENERAL

1. A veering of wind with height occurs over all areas.
2. The geostrophic wind, as measured by the contour spacing, increases with height over all areas.
3. The Showalter stability index [2] varies from -1 in area III to $+2$ in area V.

SURFACE CHARTS

1. The mean dew point over the center of the areas

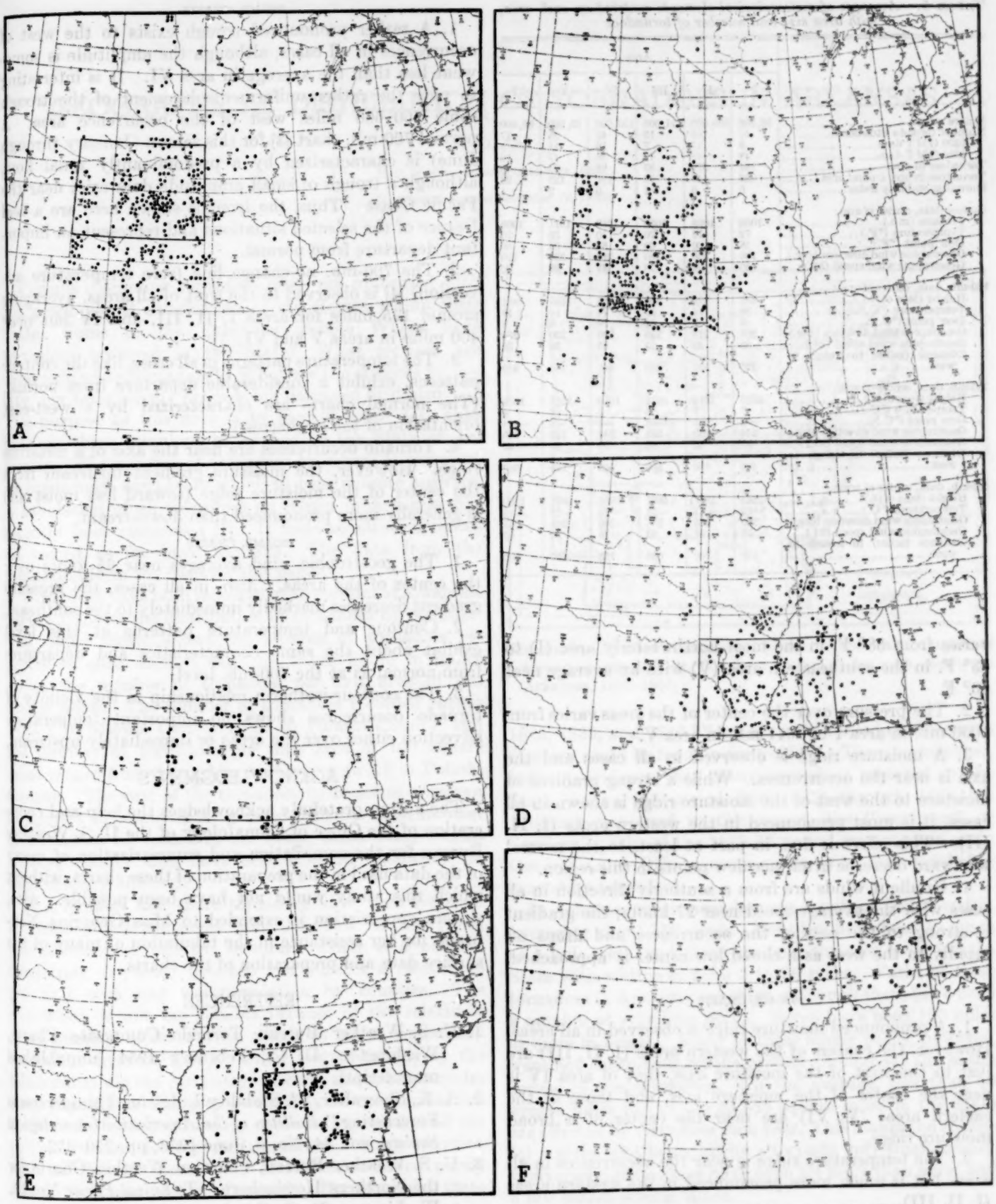


FIGURE 8.—Maps showing locations of all reported tornadoes during the time periods selected from each area (outlined). (A) Area I, (B) Area II, (C) Area III, (D) Area IV, (E) Area V, and (F) Area VI.

TABLE 1.—*Averages of meteorological elements centered on each area, with area size and number of tornadoes*

	Area					
	I	II	III	IV	V	VI
Square miles	95,000	100,000	124,000	103,000	95,000	95,000
Number tornado situations	57	66	19	42	28	17
0300 GMT data	8	17	7	16	11	1
1500 GMT data	49	49	12	26	17	16
Tornadoes in area	164	279	32	95	94	40
Tornadoes in and around area	366	449	74	191	128	98
Showalter stability index	0	0	−1	0	2	1
Surface data, center of area:						
Pressure (mb.)	1006	1008	1008	1010	1011	1008
Temperature (°F.)	72	72	70	70	70	70
Dew point (°F.)	58	60	60	63	63	60
Geostrophic wind direction (deg.)	200	200	180	210	230	220
Geostrophic wind speed (kt.)	30	24	20	32	28	20
850-mb. data, center of area:						
Height (tens of ft.)	476	479	480	485	493	481
Temperature (°C.)	16	15	15	14	14	13
Dew point (°C.)	9	9	10	10	8	8
Geostrophic wind direction (deg.)	205	215	230	220	230	230
Geostrophic wind speed (kt.)	32	30	25	35	30	35
Distance (miles) to trough to west	225	325	250	400	550	450
700-mb. data, center of area:						
Height (tens of ft.)	1010	1014	1011	1010	1018	1009
Temperature (°C.)	7	7	6	5	4	4
Dew point (°C.)	−3	−5	−6	−5	−4	−4
Geostrophic wind direction (deg.)	225	230	235	240	240	235
Geostrophic wind speed (kt.)	35	30	40	50	40	35
Distance (miles) to trough to west	400	650	500	540	750	600
500-mb. data, center of area:						
Height (tens of ft.)	1883	1887	1887	1884	1891	1880
Temperature (°C.)	−12	−13	−13	−13	−12	−13
Geostrophic wind direction (deg.)	230	235	235	240	245	245
Geostrophic wind speed (kt.)	55	55	60	75	70	60
Distance (miles) to trough to west	650	700	600	750	850	600

varies from 58° F. in the most northwesterly area (I) to 63° F. in the southeastern area (V) with an average near 60° F.

2. The pressure over the center of the areas varies from 1006 mb. in area I to 1011 mb. in area V.

3. A moisture ridge is observed in all cases and the axis is near the occurrences. While a strong gradient of moisture to the west of the moisture ridge is shown in all cases, it is most pronounced in the western areas (I, II, III). This effect is due, in part at least, to the normal westward decrease in surface dew points in this region.

4. Gradient winds are from a southerly direction in all cases with the average speed near 27 knots; the gradient is strong to the east of the occurrences and drops off rapidly to the west as a closed low center is approached.

850-MB. CHARTS

1. A pronounced moisture ridge is observed in all areas. However, the centers of the western areas (I, II, III) are just to the west of the moisture axis, that of area IV is near the center of the moisture axis, and those of the eastern areas (V, VI) are near the center of a broad moisture ridge.

2. The temperature ridge is near the occurrences in all areas but is much more pronounced in the western areas (I, II, III).

3. A trough of low pressure is observed to the west and the distance varies from 250 miles in areas I and III to near 500 miles in area V.

700-MB. CHARTS

1. A rather pronounced trough exists to the west of occurrences in all cases, although the amplitude is somewhat less than the average in area VI. It is interesting to note the rather uniform displacement of the trough some 500–600 miles west of the occurrence area. A normal 700-mb. chart [3] for this season (January through June) is characterized by a predominantly zonal flow, although a trough of small amplitude does exist near the Pacific Coast. Thus, the troughs shown here are a real feature of the selected situations and represent an important departure from normal.

2. The 700-mb. no-change line (zero temperature advection) [4] is observed to the west of all areas, averaging around 125 miles for areas I, II, III, and IV but near 400 miles in areas V and VI.

3. The temperature patterns in all cases, like the contour patterns, exhibit a considerable departure from normal. (The normal charts are characterized by a west-east orientation of the isotherms.)

4. Tornado occurrences are near the axis of a moisture ridge. However, the moisture gradient upstream from the center of the moisture ridge (toward less moist air) is generally more pronounced than downstream.

500-MB. CHARTS

1. The geostrophic wind averages near 65 knots over the center of the areas. Also, in all cases, the pressure gradient decreases markedly immediately to the southeast.

2. Contour and temperature patterns at this level exhibit about the same characteristics and departures from normal as at the 700-mb. level.

3. The contour-isotherm relationship in the vicinity of tornado occurrences shows no important temperature advection either over the areas or immediately upstream.

ACKNOWLEDGMENTS

The author gratefully acknowledges the help and cooperation of the Office of Climatology of the U. S. Weather Bureau for the compilation and summarization of many of the data used in the preparation of these charts, without which this study would not have been possible. Also, sincere appreciation is extended to Miss Georgina Neubrand for her assistance in the tabulation of many of the surface data and preparation of the charts.

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GEOGRAPHICAL DISTRIBUTION OF TORNADOES IN ARKANSAS

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[Manuscript received December 19, 1955]

Persons discussing tornadoes often are concerned with the geographical distribution of the storms within their State. Some of the questions include: Where have tornadoes occurred in the State? What sections are most subject to tornadoes? What are the chances for my city, my farm, or my home being damaged or destroyed? The purpose of this note is to present some data that bear on these questions as applied to the State of Arkansas. The number of tornadoes on record is however, an inadequate sample on which to base definite answers. A tabulation of all tornadoes on record in Arkansas has recently been completed [1]. It includes all occurrences on record as far back as 1823. The data from the tabulation form the basis for this paper.

Tornadoes have been reported in all sections of Arkansas. Figure 1 shows the distribution of tornadoes by counties. The upper figure shows the number of tornadoes reported in each county, and the lower figure in italics shows the number of tornadoes per unit area of 100 square miles. The number of tornadoes recorded ranges from 1 in Marion County to 29 in Pulaski County, and the number of tornadoes per unit area of 100 square miles ranges from 0.2 in Marion County to 3.7 in Pulaski County. The sum of the tornadoes by counties as shown in figure 1 is considerably greater than the total number of tornadoes on record in the State, since many storms crossing county lines have been counted separately for each country affected.

It is evident that more tornadoes have been reported in more populated areas and the least in the rural, mountainous, or forested sections. There is a positive correlation ($r=0.45$) between the number of tornadoes per unit area and the population by counties. The correlation is not too reliable because of the relatively small number of cases upon which to make comparison (probable error is 0.09). Other factors modifying the relationship are the percentage of rural and urban population, population changes, availability of communication facilities by which tornadoes could be reported, and the period of record for reported tornadoes. Some counties, such as Pulaski, have more tornadoes recorded partly due to a longer period of record. For example, three tornadoes in the Little Rock area (Pulaski County) in

FIGURE 1.—Number of tornadoes (upper number) and number of tornadoes per 100 sq. mi. (lower number) for each county in Arkansas, 1923–1955.

1823, 1830, and 1840 [2] are the only tornadoes for which mention could be found prior to 1853. There is, however, indirect evidence that many tornadoes occurred in the State during the period from 1829 through 1854 [3]. Although not used in this report, the "hurricane" or "cyclone" paths of the 1829–54 period, as noted on early General Land Office survey maps, were very probably caused by tornadoes.

In Arkansas most tornadoes are ¼ mile or less in width, averaging about 350 yards. Very few have been as much as a mile wide, and there are only three on record in the State with widths of from 2 to 2½ miles. Paths of most tornadoes in Arkansas are short, although there have been a number of very long paths. Seven have been 100 miles or more in length. Many of these longer paths, however, were not continuous on the ground throughout the entire course of the tornadoes. On the average, less than 10 square miles out of the 53,850 square miles in the State are affected by tornadoes each year. This makes the chance for a given spot being hit by a tornado very small indeed. Conversely, some areas have been hit more than once, and a few places several times.

Figure 2 shows the tornado paths in Arkansas from 1879 to October 12, 1955, plotted on a topographic base

[1] Present address: Weather Records Processing Center, Kansas City, Mo.

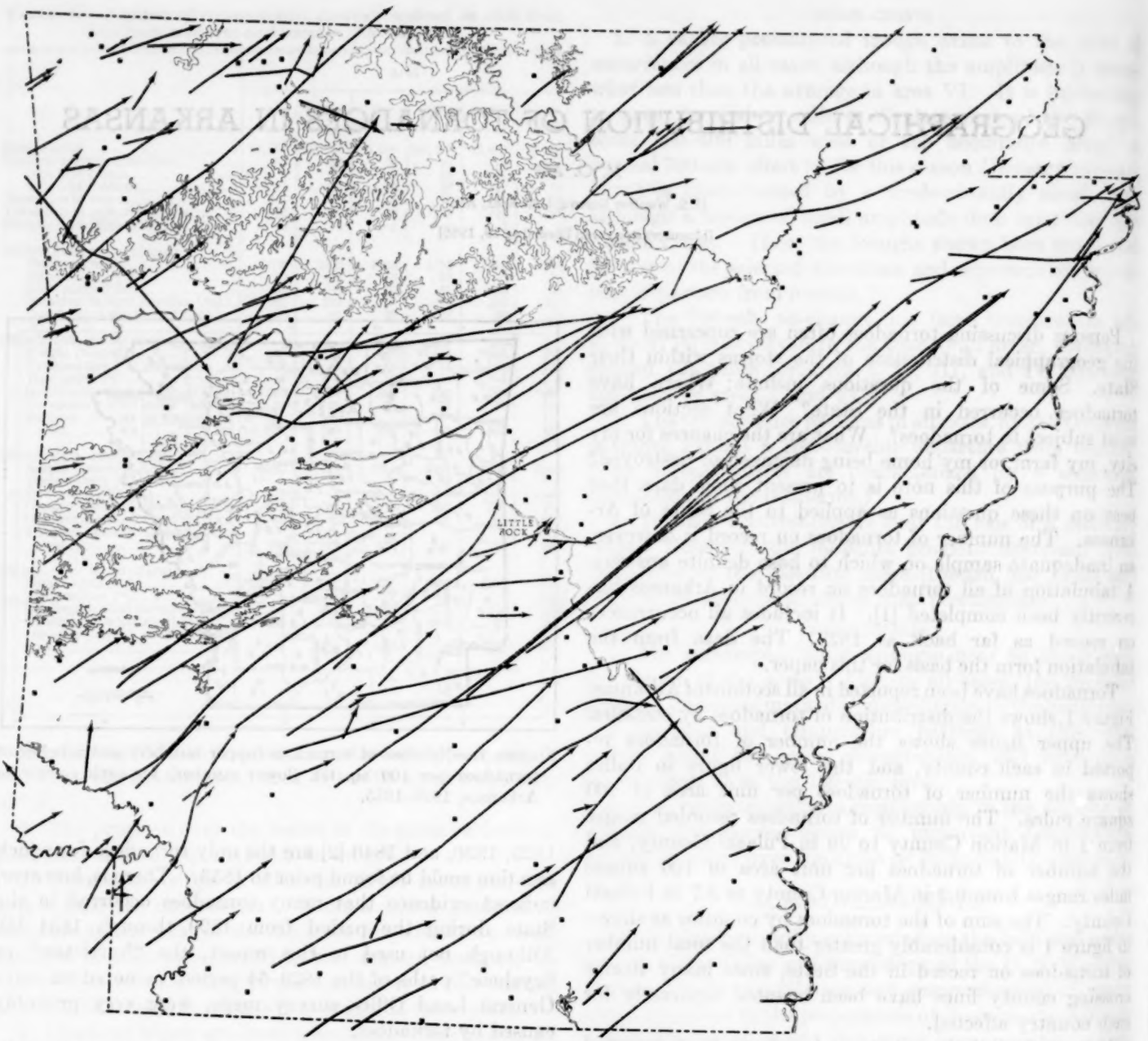

FIGURE 2.—Tornado paths in Arkansas, 1879 to October 12, 1955. Small squares show occurrences whose paths were too short to track. Thin solid lines are the 1,000- and 2,000-ft. contours.

map. Locations of tornadoes with short paths are shown by squares while longer paths are shown by lines with arrows indicating the direction of movement. Despite the irregular topography of much of the State, the prevailing direction of most tornadoes is from southwest to northeast; in fact the percentage of tornadoes from the southwest in Arkansas is 71.6 as compared with the nationwide average of 61.4 percent from that direction [4]. From figure 2 there appears to be a concentration of tornado occurrences in an area in east-central Arkansas a short distance east of the boundary of the Gulf Coastal Plain. To the north and west of the Gulf Coastal Plain boundary, which extends across the State from the southwest to northeast, the land is higher and hilly, while to the south and east of this line lies the low delta country. Another concentration of tornado paths seems to be in the Arkansas River Valley to the north of the Arkansas River and south of the Boston Mountains and the higher elevations of the Ozarks. These areas of seemingly greater tornado frequency were mentioned by Cole [5] in 1927. A number of tornadoes since that time have occurred in these same areas, including the most destructive day on record in the State, March 21, 1952, when three tornadoes left in their long paths, 111 dead, 772 injured, and 6¾ million dollars

property damage. While it appears some areas in the State may be more subject to tornadoes than others, it is believed the number of tornadoes of record so far is insufficient for an adequate sample on which to base definite statements.

There are 38 cities or towns in Arkansas, where, or near where, three or more tornadoes have occurred since 1879. In the Little Rock area there have been 12 tornadoes; 9 of these occurred since 1879, and 3 more than a century ago. The tornadoes in the Little Rock area since 1879 struck in different sections of the city although the storms of 1916 and 1923 were close together and covered the same ground for part of their paths. Despite the number of tornadoes on record in Little Rock, only a small part of the city area has actually been affected. In the Fort Smith area, 8 tornadoes have been reported, including the one that caused 52 deaths and much damage on January 12, 1898. At least two of these tornadoes struck in exactly the same section of downtown Fort Smith. Texarkana has experienced 8 tornadoes, three of which struck in the College Hill section in the eastern part of the city.

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THE WEATHER AND CIRCULATION OF APRIL 1956 [1]

A Cold Month with a Retrograding, Blocking Surge

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1. INTRODUCTION

During April 1956 an intense blocking wave slowly retrograded across North America, and the United States experienced one of its most severe Aprils on record. Spring weather is frequently extreme and variable, but this month these characteristics were intensified by the strong blocking action. Cold waves, record late snow, duststorms, local floods, extended and alleviated droughts, damaging high winds, and tornadoes were reported by many stations throughout the country.

In this review, the monthly mean circulation and its evolution throughout the month is discussed with emphasis placed on the blocking. This is followed by a discussion of the monthly weather. First the monthly average is considered, and then it is separated into shorter periods to show the large variations which occurred during the month. Tables of unusual weather phenomena are shown to illustrate the great variability of this April's weather.

2. GENERAL CIRCULATION

THE MONTH AS A WHOLE

The basic monthly mean 700-mb. pattern (fig. 1) over North America consisted of a stronger than normal ridge in western Canada, a strong trough in central Canada extending south-southeastward through Maine into the western Atlantic, and a low-latitude trough over southern California. These features combined to give a weak confluence zone through the central United States and a strong, northwesterly flow from the Yukon into the southeastern United States. The 700-mb. monthly mean patterns for April and March 1956 [1] were rather similar in the Western Hemisphere, except that during April there was a strong ridge in the Greenland region. In fact, the largest positive height anomaly (+370 ft.) for April was observed near Greenland. This positive anomaly coupled with below normal heights in eastern United States was an indicator of the blocking that prevailed during the month. Similar blocking regimes were responsible for cold, stormy April weather in the United States during 1950 [2] and 1953 [3].

The mean sea level chart (Chart XI) shows a significant belt of high pressure from the Arctic north of Alaska stretching southeastward to Florida. This delineates the path of several cold anticyclones which were steered by the upper-level, northwesterly flow into southeastern United States. The elongated Low extending from Greenland to the Great Lakes was a reflection of the daily, cold cyclones that moved along the axis of this mean Low (Chart X). A deeper than normal Low appeared in the Southwest, east of the upper level trough through California.

The geostrophic relative vorticity at 700 mb. (fig. 2) had a field which resembled the mean sea level isobaric field as noted by Klein in an early article of this series [4]. Cyclonic conditions existed in the Southwest and Northeast with a maximum center located over the Great Lakes. The upper flow was anticyclonic in the western ridge and in the Southeast.

The mean 700-mb. jet streams (fig. 3A) were located near the normal positions with one important exception. The northern branch in western North America which normally flows over Washington and Montana (see dashed line in figure 3A) was displaced 13° of latitude northward to the Yukon, from where it extended southeastward into the United States. This jet stream, which had wind speed greater than normal from the Arctic to Georgia (fig. 3B), was instrumental in advecting cold air into the Central and Eastern States at a rapid rate. The absence of a westerly jet stream over the Northwest, where wind speed averaged 3 m. p. s. below normal, had a pronounced desiccative effect on the weather in the windward areas. In the Southeast, winds were 4 m. p. s. faster than normal at the 700-mb. level. Generally in April lapse rates are steep and vertical mixing is pronounced; consequently, some of the above normal momentum at high levels may have been transported to the surface. This is attested by the strong, gusty surface winds which persisted in the Southeast. Many stations reported above normal average wind speeds and some reported damaging windstorms.

The cyclones of April traversed North America along two principal west to east tracks. One extended across central Canada and the other across central United States (fig. 4B and Chart X). The latter was closely related

[1] See Charts I-XV following p. 178 for analyzed climatological data for the month.

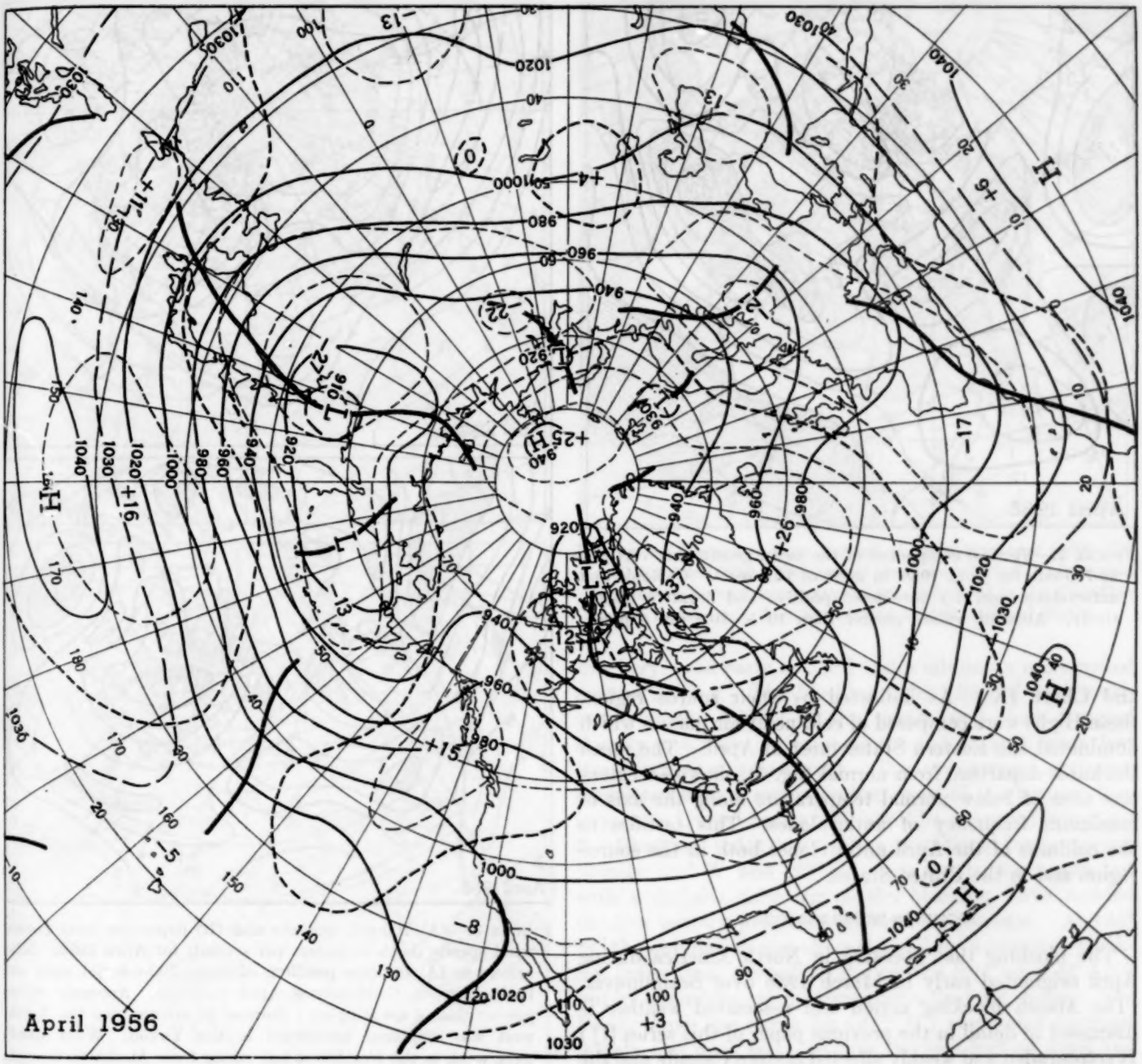

FIGURE 1.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for April 1956. A strong ridge in western Canada coupled with a deeper than normal trough near the east coast of the United States resulted in a cold April. Heights were above normal in the Davis Strait—a long-period anomaly.

to the southern branch of the jet stream (fig. 3A). Much cyclonic activity occurred in the Gulf of Alaska, but only three storms crossed the western massif. One storm passed through British Columbia and Alberta, while the other two moved northeastward through the Yukon. There was a great deal of cyclogenesis in and east of the mountains. In the United States many Nevada and Colorado Lows formed and moved eastward. Early and late in April the storms moved northeastward through the Great Lakes along the preferred seasonal track. However, during the middle of the month, when blocking was most pronounced, deep storms were deflected southward in eastern United States. Knoxville, Tenn., and Vicksburg, Miss., observed new record low sea level pressures for April on the 15th. (For a detailed study of one of the Southeast storms see article by McQueen and Rammer elsewhere in this issue.) Cyclonic activity was also prevalent in the western Atlantic, just east of the mean trough.

Nearly all the anticyclones affecting the United States in April originated in western Canada and Alaska or were break-offs of cold air masses from Canada which first appeared as closed centers in the Southern Plains (fig. 4A

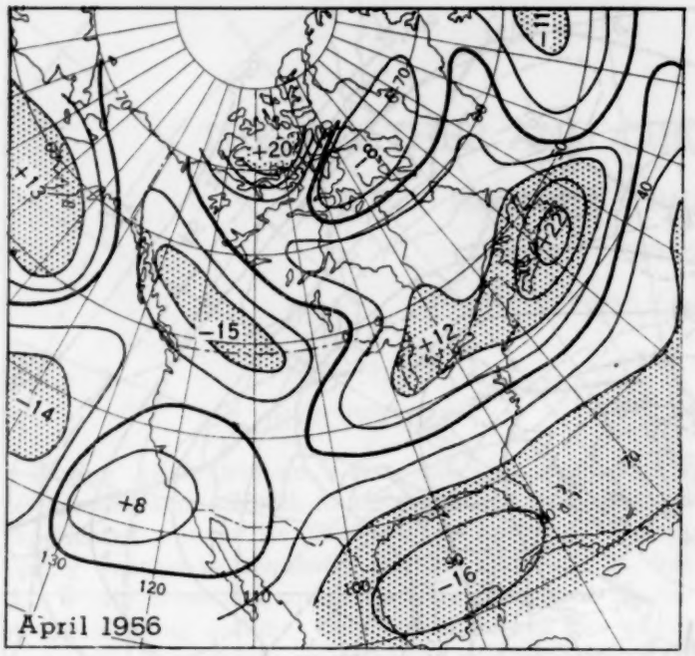

FIGURE 2.—Vertical component of the mean geostrophic vorticity at 700-mb. for April 1956, in units of 10^{-6} sec^{-1}. Cyclonic and anticyclonic vorticity considered positive and negative respectively. Absolute values greater than 10×10^{-6} are stippled.

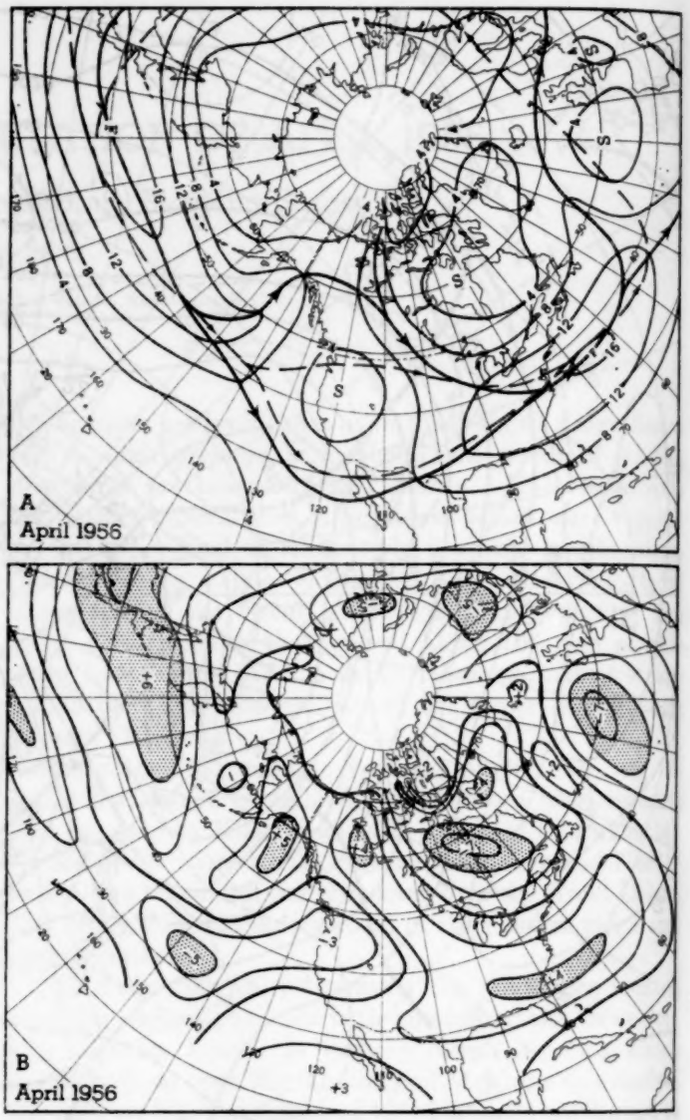

FIGURE 3.—(A) 700-mb. isotachs and (B) departure from normal wind speeds (both in meters per second) for April 1956. Solid arrows in (A) indicate positions of mean 700-mb. jet axes, and broken arrows their normal April positions. Anomaly values greater than 4 are stippled. Normal jet stream over the Northwest was displaced northward to the Yukon. Wind speeds were weak in the Northwest but strong from Alaska to Georgia.

and Chart IX). As indicated by their source region, these Highs were composed of cold polar air masses which dominated the Eastern States most of April. The mean thickness departure from normal (fig. 5), shows an extensive area of below normal temperature along the axis of maximum frequency of anticyclones. This testifies to the coldness of the April anticyclones both in the source region and in the United States.

EVOLUTION WITHIN THE MONTH

The blocking that operated in North America during April originated early in March 1956 over Scandinavia. (The March blocking action and associated weather is discussed in detail in the previous paper of this series [1].) It retrograded and weakly affected eastern Canada and the western Atlantic early in April. Five-day mean 700-mb. heights for March 31–April 4, 1956 (fig. 6A) were as much as 360 feet above normal in the Davis Strait and below normal to the south over the Atlantic. Positive height anomalies over eastern Canada have been a long-period and persistent feature of the circulation and their continued effects on the circulation and the United States weather have been emphasized in many recent papers [1, 5, 6, 7].

The strong tendency for 700-mb. height to remain above normal over the Baffin Island region this April is illustrated by the quasi-stationary nature of a 5-day mean, positive anomaly center (fig. 7) which was observed during each week of the month. One manifestation of the influence of this positive center on the circulation was the negative anomaly in eastern United States which appeared early in the month and then meandered in the vicinity of the Great Lakes until the end of April. It should be pointed out that even though 700-mb. heights persisted above normal in the Baffin Island area, there was also an almost continuous rise of heights in western Canada and Alaska. Apparently the original positive anomaly over Greenland divided, and one center remained in eastern Canada while another retrograded and infected the westerlies progressively farther upstream in a manner described by Namias [8].

It was noted at the beginning of this section that the blocking observed early in April in eastern Canada (fig.

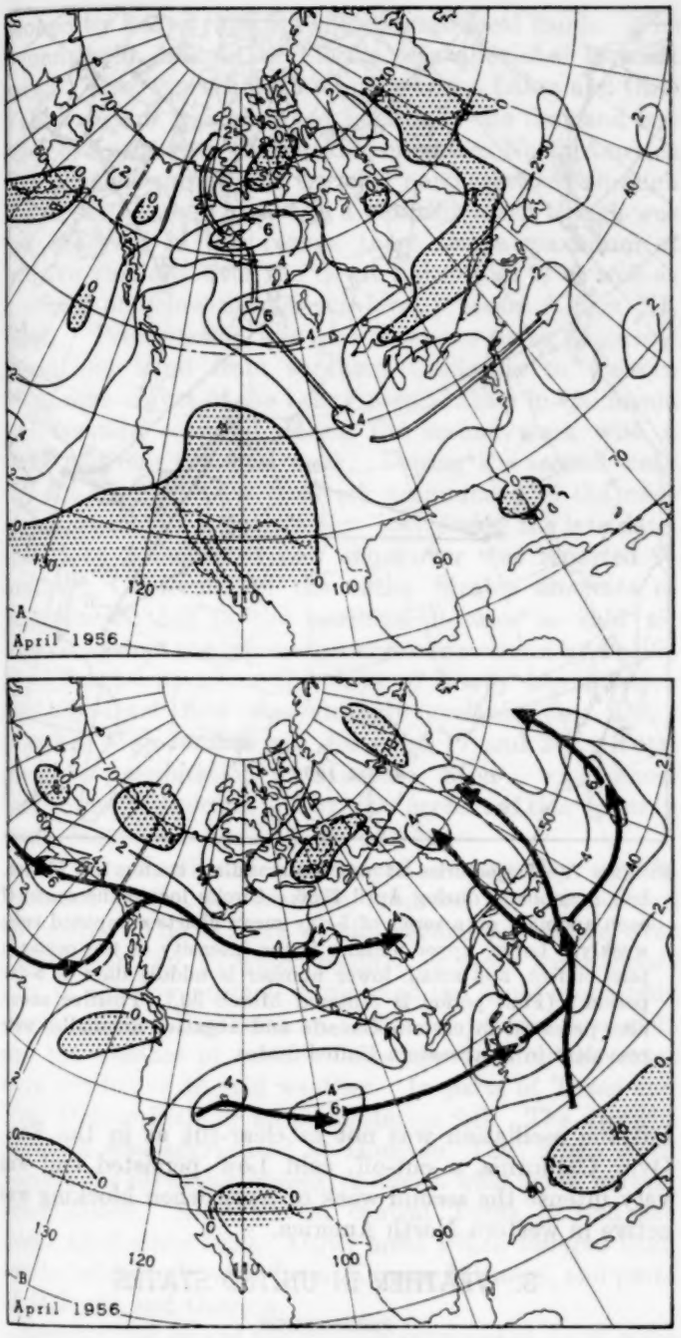

FIGURE 4.—(A) Frequency of anticyclone passages and (B) cyclone passages (within 5° squares at 45° N.) during April 1956. Zones of frequent anticyclone and cyclone passage are indicated by open and solid arrows respectively. Cold anticyclones from Canada frequently invaded the United States. Cyclones had trajectories south of normal in the East.

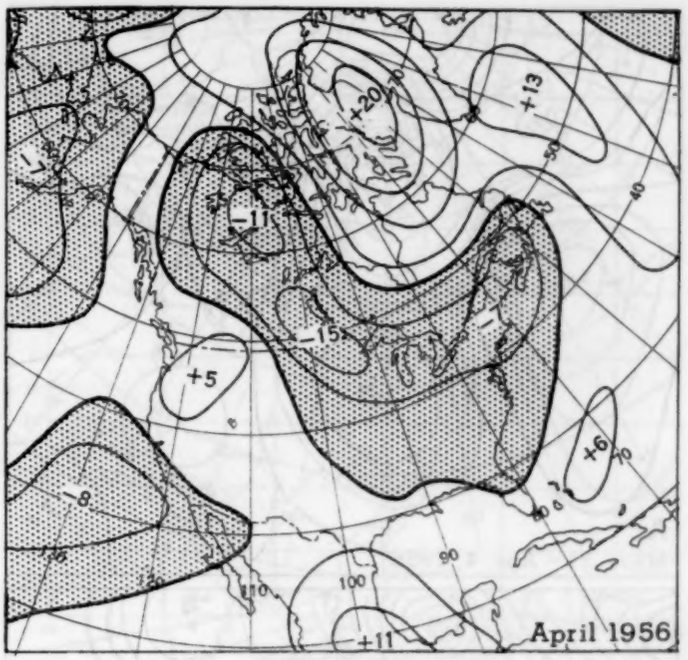

FIGURE 5.—Departure from normal of mean thickness (1000–700 mb.) for April 1956. Subnormal areas are stippled. Air masses with below normal temperatures, especially cold in the Canadian source region, spread southeastward over the United States.

6A) had retrograded from its March location. In order to illustrate the strong blocking surge that intensified during April and continued to retrograde rather slowly, a simple local blocking index was computed which essentially measures the weakness of the westerlies between 35° N. and 65° N. along a given meridian (fig. 8). In eastern North America (see the curve for 75° W.) blocking was very weak early in April and a minimum was reached around April 3. The blocking index climbed to a maximum by the middle of the month and then dropped sharply to a negative value at the end of April when fast westerly flow was dominant. This pronounced cycle was associated with a corresponding cycle of the temperature in eastern United States which will be discussed in section 3. Blocking index curves for meridians farther west, namely 125° W. and 165° W., show similar variations but with a definite time lag as the blocking wave molded the flow pattern progressively farther upstream. At 125° W. the circulation was characterized by a negative blocking index (fast westerlies) during the first week of April but by a blocking regime throughout the final weeks. The Pacific flow (see curve for 165° W.) responded approximately one week later, so that the first half of April had fast westerlies and the latter half a high blocking index. The intensification and retrogression of the blocking is also disclosed in the long-period evolution of the 5-day mean positive height anomaly in Canada (fig. 6) which was initially +360 ft. but subsequently retrograded and increased to +620 ft. at mid-month (fig. 6B) when blocking reached its peak. It continued to retrograde and weakened to +400 ft. by the end of April (fig. 6C).

In connection with this blocking phenomenon a 15-day oscillation of 700-mb. heights occurred in the United States. In the East heights were above normal at the beginning and end of the month and strongly below at mid-month (fig. 6). In the mountainous areas of the West the height of the 700-mb. pressure surface essentially oscillated from below to above normal and back to below,

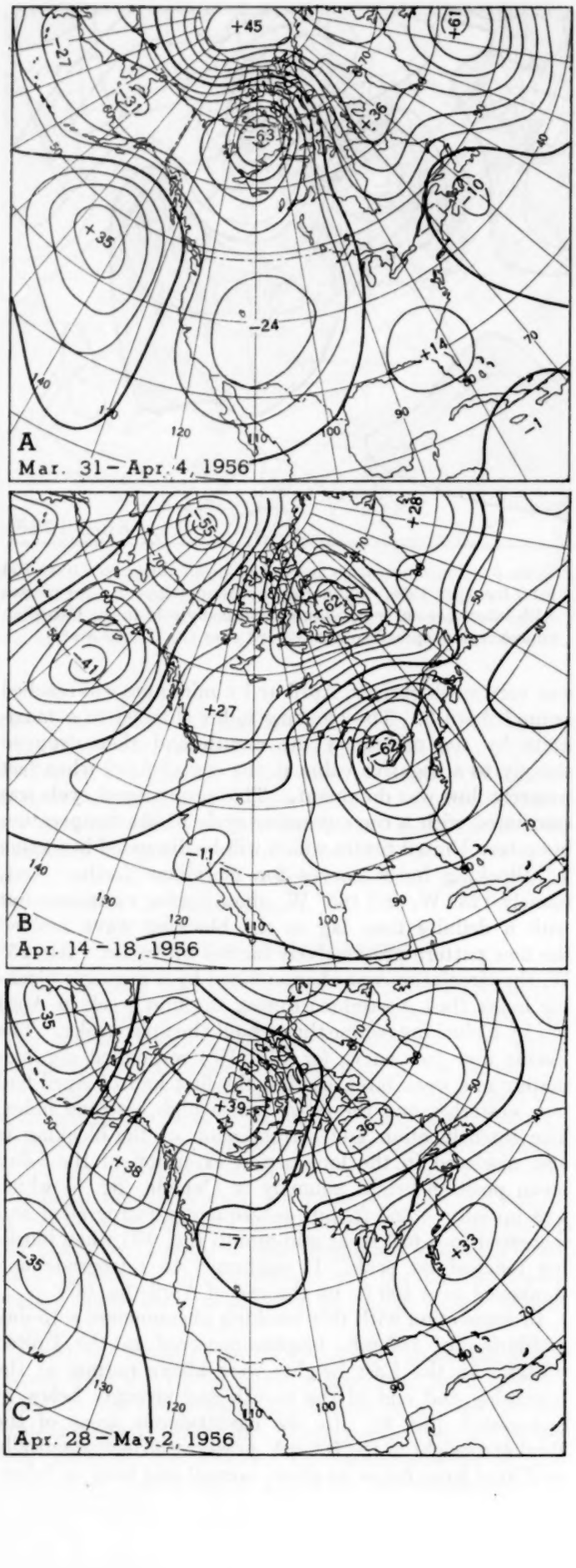

FIGURE 6.—Five-day mean 700-mb. height departures from normal in tens of feet for periods in April 1956 centered 14 days apart. Note the double oscillation of height anomaly in United States. The mid-month couplet of a positive anomaly north of a negative anomaly in eastern North America was a manifestation of the blocking action.

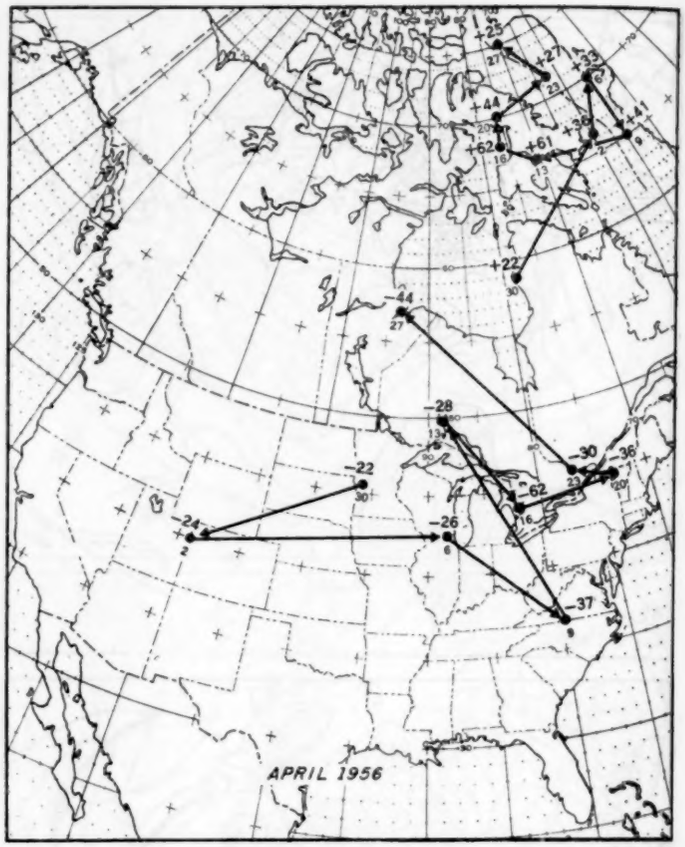

FIGURE 7.—Trajectories of two outstanding centers of 700-mb. height anomaly during April 1956. Circles locate the center of each anomaly on a series of 5-day mean charts computed twice weekly. Large, upper number is the intensity of the center in tens of feet, and small, lower number is middle date of 5-day period. (First period is centered March 30.) Positive anomalies persisted in eastern Canada and negative anomalies were prevalent in northeastern United States.

but the oscillation was not as clear-cut as in the East. Over California a cut-off, cold Low persisted and was very intense the second week of April when blocking was active in western North America.

3. WEATHER IN UNITED STATES

PRECIPITATION

The total monthly precipitation (Charts II, III) was generally plentiful east of the Mississippi River. Above normal precipitation over the Southeast occurred mainly during the first two weeks, though spotty but heavy amounts were observed along the Gulf Coast and Florida the last week. The drought in southeastern Texas was

broken by heavy rains which produced local floods. The 4-month-old drought in Florida was alleviated in most areas. Heavy precipitation in the Great Lakes and Ohio Valley regions was observed essentially the first and last week of April, when the blocking in eastern North America was relaxed, and storms traveled northeastward through the Great Lakes. Although a monthly mean trough was not observed in this region, there was a maximum of relative vorticity over the Great Lakes (fig. 2) as well as a center of below normal sea level pressure (Chart XI, inset). Precipitation was also in excess along a narrow meridional band from southern California to western Montana. Most of the heavy precipitation in California and Nevada occurred during the second week with a small addition the final week. During the second week the cut-off, cold Low was very pronounced in the mid-troposphere. It is noteworthy, considering the late date, that 7 to 8 inches of new snowcover was reported in southern California on the 13th. Sizable amounts of precipitation fell in the northern Rockies as cold air banked against the mountains and was overrun by Pacific air. Furthermore, on the days of heavy precipitation the high-level flow was strongly cyclonic (see Daily Weather Map for 500 mb. for April 17 and 24). Total monthly precipitation at Missoula, Mont., was almost three times the normal and over 90 percent of this monthly total occurred on April 16, 17, and 24.

The far Northwest experienced a very dry month; Spokane, Wash., for example, recorded the driest April on record. The absence of the normal jet stream over Washington (fig. 3) which resulted in mean wind speeds 3 m. p. s. below normal, diminished the usual orographic precipitation. Furthermore both anticyclonic flow aloft and the absence of surface Lows approaching the coast were conducive to arid weather. In parts of Texas and New Mexico little or no precipitation fell. The drought situation was aggravated at Houston, Tex., when April became the seventh consecutive month with below normal precipitation. At Waco in central Texas it was the driest April since 1920. Other areas which suffered from continued drought were Iowa, Kansas, Missouri, and parts of Alabama and Georgia.

Snowstorms, one of the weather extremes of April, were closely associated with the blocking. Widespread snowfall totaling roughly 6 to 12 inches fell over the Northeast and through the Mid-West on the 7th and 8th. In general, the amounts were records for so late in the season. In the Northeast additional snow on the 23d and 24th combined with the earlier snowfall to give many areas the snowiest April in several years, and some stations, for example Portland, Maine, considered April 1956 one of the snowiest on record. Stations in Minnesota and Wisconsin also received a record snowfall for so late in the season on the 29th.

The connection between heavy snowstorms and blocking has previously been noted [1, 9, 10]. The necessary, cold, quasi-stationary, sea level anticyclone to the north and northwest of the snow area was very pronounced on April 17, 18, and 29. (See Daily Weather Map for these dates.)

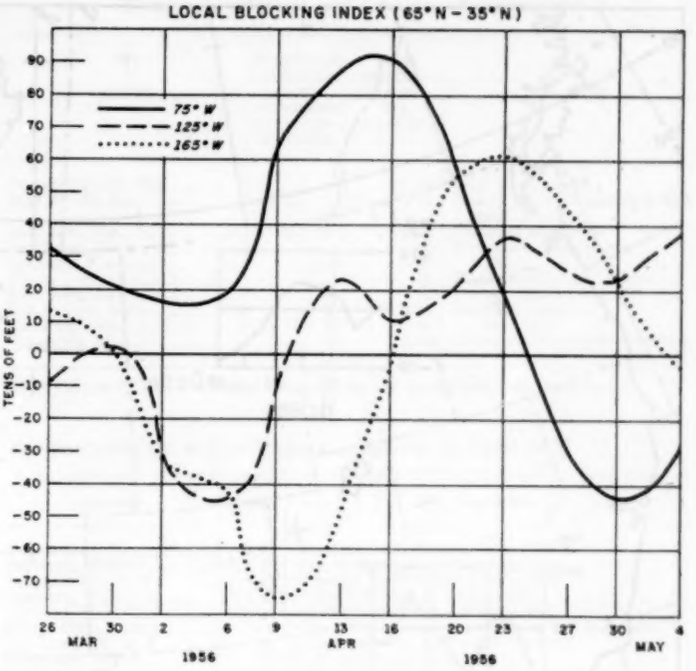

FIGURE 8.—Time variation of local blocking index in tens of feet for three meridians in the Western Hemisphere during April 1956. Index values were obtained twice weekly by subtracting the 700-mb. 5-day mean height anomaly at 35° N. from the corresponding anomaly at 65° N. Values were plotted at middle date of 5-day period. Time lag of the increase of blocking index reflects the slowly retrograding blocking surge. Large-amplitude cycle with a maximum at mid-month occurred at 75° W.

TEMPERATURE

April was essentially a cold month; temperatures averaged as low as 8° F. below normal in the extreme Northern Plains. Extremely cold periods were observed in the Southeast around the 10th and 20th and in the Northern Plains near the end of April. However, it was warmer than normal in a small area of the Northwest (Chart I). This temperature pattern is easily associated with the 700-mb. mean chart (fig. 1). Heights were below normal over most of the country except in the Northwest where the height anomaly was positive and the flow anticyclonic. Over most areas the upper flow had a stronger than normal component from the north and particularly so in the Great Plains.

Blocking action was largely responsible for cold weather during April. It operated in two rather typical ways to keep temperatures below normal. (1) When blocking was operating in eastern North America and heights of the 700-mb. pressure surface were above normal in Canada and below normal in eastern United States, the weather was cold over the eastern portion of the States, especially in the Southeast. This is similar to the relation between

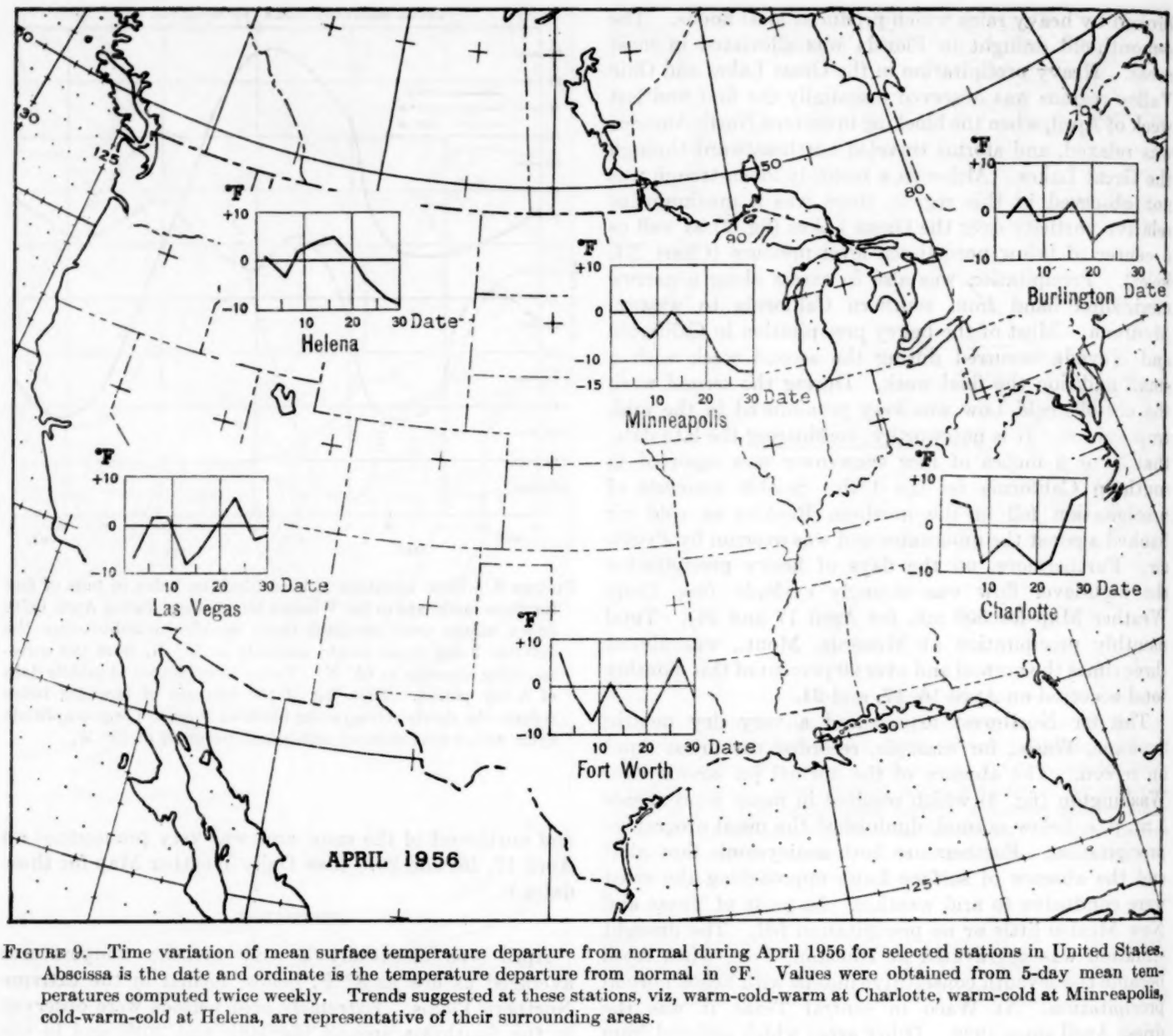

FIGURE 9.—Time variation of mean surface temperature departure from normal during April 1956 for selected stations in United States. Abscissa is the date and ordinate is the temperature departure from normal in °F. Values were obtained from 5-day mean temperatures computed twice weekly. Trends suggested at these stations, viz, warm-cold-warm at Charlotte, warm-cold at Minreapolis, cold-warm-cold at Helena, are representative of their surrounding areas.

blocking and temperature found by Rex for Europe [11]. (2) When blocking was operating farther west in Canada and the upper-level ridge over western Canada and Alaska was consequently stronger than normal, cold air was advected into the States east of the Rocky Mountains. Martin and Hawkins [12] found a large negative correlation between 700-mb. heights over western Canada and surface temperatures in the United States east of the Divide in winter.

Even though the monthly temperature average was generally below normal, there were brief warm periods. Various trends and cycles in the temperature were apparent. Graphs were therefore plotted showing the time variation of the surface temperature departure from normal for stations typical of the various areas (fig. 9).

In the Southeast (see graph for Charlotte), April started and ended warm, but the intervening period was unusually cold except for a brief warming which occurred at most stations near the 15th when warm air invaded the area ahead of the deep cyclone. The out-of-phase relation between this temperature variation and the blocking index at 75° W. (fig. 8) is striking. Daily mean temperatures were the lowest recorded in recent Aprils, and many new minima were established. Damaging frosts were common.

The Northeast (see graph for Burlington) experienced a temperature variation somewhat similar to the one in the Southeast, but because this area was located midway between the blocking High and Low, the relation between blocking and temperature was not clear cut. Some stations in the Northeast reported the coldest April since 1943 and 1944 and this month was the first April since

1950 that temperatures averaged below normal in most areas of the Northeast.

The Southern Plains and the Mid-West (see graph for Fort Worth), in proximity to the jet stream and frontal zone, underwent extreme temperature variations. For example, the daily average temperature at Kansas City, Mo., was 22° F. below normal on the 23d and 17° F. above normal on the 27th. Several maximum and minimum temperature records were broken in the Mid-West and in the Southern Plains respectively. Superimposed upon these large short-period variations was an overall cooling, in the departure from normal sense, during the month.

In the Northern Plains the almost continuous cooling trend during April is more conspicuous (see graph for Minneapolis). The first few days were spring-like, but the rest of the month was more typical of winter. As the blocking surge slowly retrograded during the month, the ridge over western Canada and Alaska intensified and cold Arctic air was advected into the United States.

The temperature trend, cool to warm to cold, in the Northwest (see graph for Helena) was generally out-of-phase with the trend in the Southeast. The temperature departure is difficult to relate to the blocking although the cold at the end of the month was definitely a consequence of the strong high-latitude ridge to the northwest.

In the Southwest (see graph for Las Vegas) the temperature was rather variable and no trends were apparent.

WEATHER HIGHLIGHTS

Many of the weather heterogeneities of April have already been mentioned. However, typical reports of interesting phenomena from the various areas of the United States have been tabulated in brief form in tables 1–4. The extreme cold, late snowstorms, and windy weather have already been emphasized. It should further be pointed out that the high winds combined with the arid condition in the Southern Plains to produce some severe duststorms. For example, a duststorm caused complete darkness at 2:30 p. m. local time April 2 at Midland, Tex. The first part of April experienced a large number of tornadoes and severe storms, but as cold air flooded the eastern half of the country and the trough stagnated off the east coast, conditions became unfavorable for severe storms and only a few were reported. Late in the month maritime tropical air returned to the Southeast and another outbreak of severe storms occurred. Early, unofficial reports of the number of tornadoes in the United States by weeks are: April 2–8, 71; April 9–15, 15; April 16–22, 0; April 23–29, 22. The days with greatest severe local storm activity were April 2, 3, 14, 15, and 28. The tornadoes of April 2 and 3 are discussed in an article by Hanks and Neubrand elsewhere in this issue.

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TABLE 1.—*Floods and droughts of April 1956*

Station	Number of consecutive months with below normal precipitation	Total monthly precipitation (inches)	Remarks
Corpus Christi, Tex.		*8.04	New April record.
Fort Worth, Tex.		3.12	Heavy rains on 29th and 30th ended drought.
Lakeland, Fla.	4	3.26	Drought alleviated.
Pendleton, Oreg.		.01	Driest April on record.
Spokane, Wash.		.08	Do.
Waco, Tex.		.65	Driest April since 1920.
Key West, Fla.		.12	Driest April on record.
Des Moines, Iowa.	7	.30	Drought extended.
Houston, Tex.	7	1.84	Do.
Columbia, Mo.	6	2.25	Past 6 months driest on record.

*At Corpus Christi 7.19 inches of rain on the 23d caused extensive flooding.

TABLE 2.—*Major snowstorms of April 1956*

Station	Dates	Remarks
Concord, N. H.	8, 23	April snowfall greatest since 1933.
Portland, Maine	7, 8, 23	One of snowiest Aprils on record.
Binghamton, N. Y.	7, 8, 23	Greatest April snowfall since 1943.
Scranton, Pa.	7, 8, 23	Second greatest April snowfall.
Trenton, N. J.	8, 23	April snowfall greatest since 1924.
Dodge City, Kans.	8, 9	One of the heaviest snows for so late in season.
Atlantic City, N. J.	24	Latest snowfall in 73 years of record.
Rochester, Minn.	29	Late season record snow.
La Crosse, Wis.	29	4½ inches of snow.
Akron, Ohio	7, 8, 17, 23, 24	April snowfall greatest since 1924, 4 times the average for past 10 years.
Milford, Utah	1, 2, 13	Heaviest April snowfall since 1931.
Tucson, Ariz.	2	First measurable snowfall in April since 1895.

TABLE 3.—*Surface wind phenomena and duststorms of April 1956*

Station	Date	Wind speed (m. p. h.)	Remarks
Victoria, Tex.	15	51	Highest gust reported.
Atlanta, Ga.	15	68	Fastest mile.
Columbus, Ga.	15		Widespread damage due to high winds.
Knoxville, Tenn.	15	69	Fastest mile.
Mobile, Ala.	10	58	High winds, minor damage.
Toledo, Ohio.	3	72	Peak gust of 84 m. p. h. caused much damage.
Roanoke, Va.	7		Severe windstorm with hail.
Richmond, Va.			Windiest April since 1943.
Oak Ridge, Tenn.			Highest average windspeed on record (7.7).
Jacksonville, Fla.			Highest average windspeed in 23 years (10.6).
Midland, Tex.	2		Duststorm caused complete darkness at 2:30 p. m.
San Antonio, Tex.	3, 9		Dust on several other days.
Roswell, N. Mex.	2	65	Worst duststorm of season.

TABLE 4.—*New temperature records made in April 1956*

Station	Date	Maximum (° F.)	Minimum (° F.)	Remarks
Concord, N. H.	.....	.....	.....	Coldest April since 1944.
Burlington, Vt.	.....	.....	.....	Coldest April since 1950.
Frederick, Md.	.....	.....	.....	Coldest April since 1943.
Providence, R. I.	13	.....	26	Record for this date.
Newark, N. J.	21	.....	32	Do.
Harrisburg, Pa.	25	.....	30	Late season minimum.
Raleigh, N. C.	21	.....	28	Do.
Fargo, N. Dak.	28	.....	16	Record for this date.
Rochester, Minn.	30	.....	11	Late season minimum.
La Crosse, Wis.	30	.....	17	Do.
Springfield, Ill.	23	.....	23	Record for this date.
Wichita Falls, Tex.	11	.....	31	Late season minimum.
Walla Walla, Wash.	6	.....	31	Record for this date.
Dallas, Tex.	11	.....	38	Do.
	27	88	.....	Do.
Charlotte, N. C.	21	.....	31	Late season minimum.
	30	89	.....	Record for this date.
Chattanooga, Tenn.	19	.....	20	Do.
	28	88	.....	Do.
Richmond, Va.	4	86	.....	Do.
Miami, Fla.	7	93.4	.....	Early season maximum.
Dodge City, Kans.	26	94	.....	Record for this date.

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TORNADOES OF APRIL 2 AND 3, 1956

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ABSTRACT

A discussion of the synoptic situation leading to the occurrence of tornadoes on April 2 and 3 is presented. It is found that approximately the same instability and low-level moisture conditions existed on April 1, 2, and 3. Reasoning from the vorticity equation and upper-level charts suggests that a strong vertical motion field was the significant factor present on April 2 and 3, which was not present on April 1, a day without tornadoes.

1. INTRODUCTION

Tornadoes killing nearly 50 people, injuring hundreds, and causing damage in the millions cut a swath of destruction through a dozen Midwest States on April 2 and 3, 1956 (fig. 1A) in the largest family outbreak of tornadoes between January and May of 1956. Associated with a deep low pressure system moving eastward from Colorado, the first of these storms occurred in central Kansas shortly after 1800 CST, April 2. Over 20 tornadoes, numerous damaging wind storms, and hail were reported that night from southern Oklahoma, through central and eastern Kansas, extreme southwestern Missouri, and as far north as southwestern Iowa (fig. 1B). Five persons were killed in the tornado that moved through Drumright, Okla., about 2130 CST. In the afternoon and evening of the following day, tornadoes occurred again in a wide band extending north from Mississippi through western Tennessee (fig. 1C) and on both sides of Lake Michigan into central Wisconsin and western Michigan. The greatest loss of life in these storms was reported in Michigan where 17 persons were killed at Hudsonville and 6 persons died at Standale, a suburb of Grand Rapids. In all, over 60 tornadoes, not including several waterspouts on Lake Michigan, were reported on these two days.

The purpose of this paper is (1) to present the macroscale synoptic features which appeared to be most important in producing the tornado activity; (2) to bring out some of the significant similarities and differences between synoptic conditions on April 1 and 2, 1956; and (3) to present certain mesoscale features detected by radar and sferics prior to and during tornado activity.

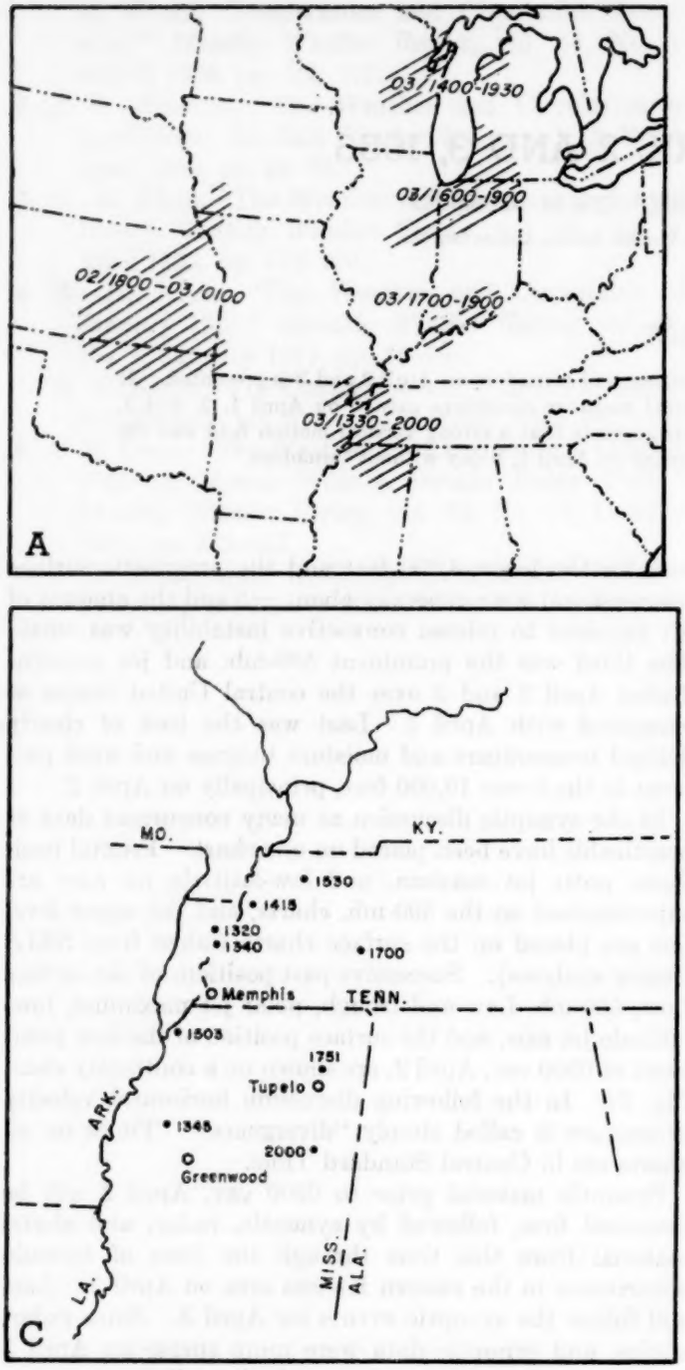
Several factors of particular interest were noted for the period of April 1–3, 1956. The first was the large amount of low-level moisture present over the area of Texas, Oklahoma, and Kansas as early as the morning of April 1, the day before tornado activity. Second was the great instability present (mostly as a result of moisture). Lifted indices [1] (a measure of stability based on average moisture for the lower 3,000 feet and the prognostic surface temperature) were generally about −5 and the amount of lift required to release convective instability was small. The third was the prominent 500-mb. and jet patterns during April 2 and 3 over the central United States as compared with April 1. Last was the lack of clearly defined temperature and moisture tongues and wind patterns in the lower 10,000 feet, principally on April 2.

In the synoptic discussion as many concurrent data as practicable have been placed on one chart. Frontal positions, polar jet maxima, and low-latitude jet axes are superimposed on the 500-mb. charts, and the upper level jets are placed on the surface charts (taken from SELS Center analyses). Successive past positions of the surface Low, 500-mb. Low and trough, polar jet maximum, low-latitude jet axis, and the surface position of the dew point front at 0900 CST, April 2, are shown on a continuity chart (fig. 2). In the following discussion horizontal velocity divergence is called simply "divergence." Times on all charts are in Central Standard Time.

Synoptic material prior to 0900 CST, April 2 will be discussed first, followed by synoptic, radar, and sferics material from this time through the time of tornado occurrences in the eastern Kansas area on April 2. Last will follow the synoptic events for April 3. Since radar, sferics, and synoptic data were more sparse on April 3 than on April 2, the situation on April 3 will be treated in lesser detail.

2. SYNOPTIC SITUATION PRIOR TO 0900 CST, APRIL 2

Early on April 1 a strong upper-level short-wave trough was moving from southwestern United States toward the Central Plains into a region of abundant moisture and instability which extended from the Gulf of Mexico into Kansas. This short-wave trough and associated jet maximum appeared to be moving out of a deep elongated trough centered along the west coast As the short wave moved eastward the relatively flat ridge over central United



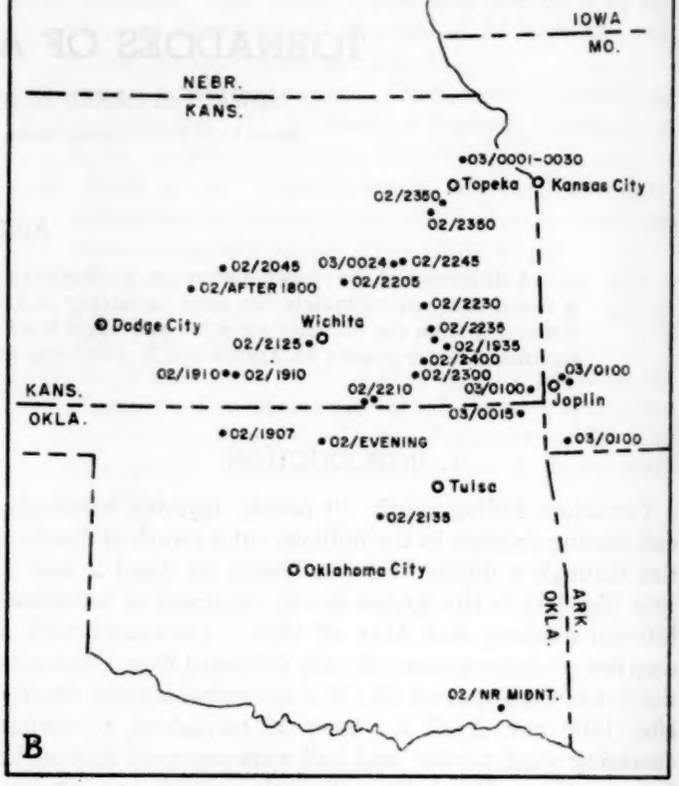


FIGURE 1.—(A) General areas of tornado activity on April 2 and 3, 1956. (B) Tornadoes in Kansas and vicinity, April 2 and 3, 1956. (C) Tornadoes in Mississippi and Tennessee, April 3, 1956.

States moved eastward slightly and increased in amplitude. By 2100 CST, April 1, the short-wave trough at 500 mb. had moved out of this larger-scale trough in a northeastward direction and by 0900 CST, April 2, to northeastern Arizona. At the surface, a large disorganized 990-mb. Low was located in southeastern Colorado. Past positions to 0900 CST indicated no motion of this Low for at least 9 hours. During this time, surface dew points in the 60's were spreading farther northward from the Gulf of Mexico.

Thunderstorms had continued from the afternoon of April 1 into the morning of April 2 prior to 0900 CST, indicating that a mechanism other than heating was producing convective activity, but, in spite of moisture and instability, was producing no tornadoes. For example, nighttime activity occurred in Iowa, Tennessee, and Oklahoma. Early on April 2, 1-inch hail was reported in Oklahoma. Central Oklahoma was still reporting thunderstorms at 0630 CST. The most likely explanation for this convective activity is a broad vertical motion field, associated with increasing amplitude of high-level troughs and ridges.

3. EVENTS SUBSEQUENT TO 0900 CST, APRIL 2

From succeeding events it was noted that the surface Low became organized as the 500-mb. Low approached from the southwest, that the low-level thermal and wind patterns were difficult to interpret, and that the movement of the high-level features into an area of abundant moisture and instability appeared to be the chief contribution to the tornado activity which followed.

EVENTS AT THE SURFACE

The surface features during the afternoon appeared to

become organized with the approach of the 500-mb. closed Low. At the surface, the 1530 CST chart (fig. 3A) indicated for the first time two definite centers, both 990 mb., one remaining in southeastern Colorado and subsequently weakening and one forming near Garden City, Kans., near the juncture of the dew point front (western edge of strong moisture gradient) and the quasi-stationary front to the north. At the time of the formation of the Low in Kansas a squall line moved northeast at about 40 knots accompanied by large hail. About 1530 CST, April 2 only two large precipitation cells were easily distinguishable by radar. One cell was followed by the 4-station sferics network of the Air Force. This cell, first detected at 1400 CST, 20 nautical miles east-southeast of Wichita, Kans., was associated with hail, and was interpreted as being possibly tornadic. Later a sferics fix was associated with large hail 20 miles west-southwest of Emporia, Kans. The largest hail reported during the afternoon near sferics fixes was 1¾ inches at 1830 CST, 5 miles north of Forbes Air Force Base, Topeka, Kans. No tornadoes were reported with these fixes.

By 1830 CST (fig. 3B) the 990-mb. center near Garden City had moved eastward, to east of Dodge City. About this time another squall line was analyzed east of the dew point front extending from Abilene, Tex., into the low center at Dodge City. Also at 1830 CST, radar indicated a line of moderate to strong echoes from 80 miles north-northwest of Grand Island, Nebr., through Russell, Kans., to a point 50 miles east of Gage, Okla. This was the squall line connected with the tornado activity that began about 1800 CST. During the next 3 hours, the surface Low near Dodge City accelerated to the northeast (between 2130 CST, April 2 and 0030 CST, April 3 it deepened 3 mb.) as it was approached by the 500-mb. Low moving from the southwest (fig. 2). By 2035 CST, April 2 (fig. 3C) the radar indicated that the squall line had lengthened rapidly to the north and south, extending from Huron, S. Dak., to 30 miles west of Lincoln, Nebr., to Hutchinson, Kans., then south-southeast to a point 30 miles east of Oklahoma City to 20 miles southeast of Mineral Wells, Tex. At 2100 CST the radar indicated the squall line was dissipating in the vicinity of the surface Low in Kansas. At this time, the squall line divided into two segments. The southern segment, which was associated with most of the tornadoes, moved eastward at 40 knots. The northern segment of the line moved east-northeastward with decreasing intensity at a speed of 25 to 30 knots. A few reports of tornadoes were received in connection with the passage of this line in extreme northeastern Kansas and extreme southwestern Iowa. The organizaton and acceleration of a separate Low into an area of greater moisture and instability appeared to be the significant surface features associated with the tornado activity.

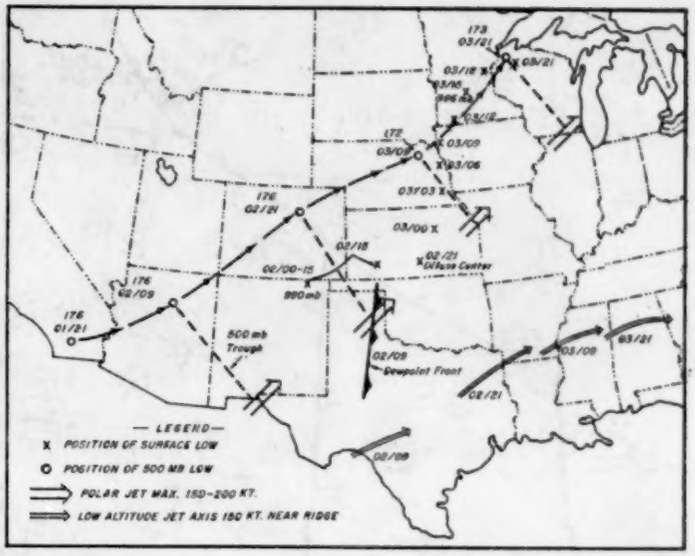

500 mb Trough
Dewpoint Front
— LEGEND —
POSITION OF SURFACE LOW
POSITION OF 500 MB LOW
POLAR JET MAX. 150-200 KT.
LOW ALTITUDE JET AXIS 150 KT. NEAR RIDGE

FIGURE 2.—Successive positions of surface Low, 500-mb. Low and trough, polar jet maximum, and low-latitude jet axis from 2100 CST, April 1 through 2100 CST, April 3, 1956. Also shown is the surface position of dewpoint front at 0900 CST, April 2.

FEATURES IN THE LOWER LEVELS

East of the surface system after 0900 CST, April 2, the lower levels were characterized by abundant moisture and instability, weak thermal patterns, and strong but indefinite wind patterns. The average mixing ratio in the lower 3,000 feet was generally 11 to 13 gm./km. and lifted indices were −5 to −10 during the afternoon. Within the large warm sector it was difficult to determine the exact location of either thermal or moisture ridges at 850 mb. or the no-change line of apparent advection at 700 mb. An important feature was the strong east-west gradient of moisture and instability in western Oklahoma. Also, the changes in the low-level wind field appeared to be somewhat erratic (fig. 4). One feature observed was the increase of the gradient level wind (low-level jet) at 1500 CST (fig. 4B) east of the dew point front. This occurred about the same time that the Low near Garden City formed. At the same time the jet in the lower levels showed little change ahead of the cold front extending into Colorado. This can be seen from the 850-mb. winds (fig. 5) which on April 2 were in most instances representative of the low-level jet. Thus, even though the low-level wind and temperature were undoubtedly important, the uncertainty in placement for this particular day made them difficult to interpret. The great instability and moisture were the most salient features in the low levels.

UPPER-LEVEL FEATURES

The features which appeared to be most important both in timing and in predicting the occurrence of tornadoes for April 2 were the short-wave trough and associated jet maximum which moved from the southwest into the Oklahoma-Kansas area (fig. 6). During this period, the jet maximum moved from near El Paso, Tex., at 0900 CST, April 2, (fig. 6A), to near Childress, Tex. by 2100 CST (fig. 6B). It appeared to move with the same speed

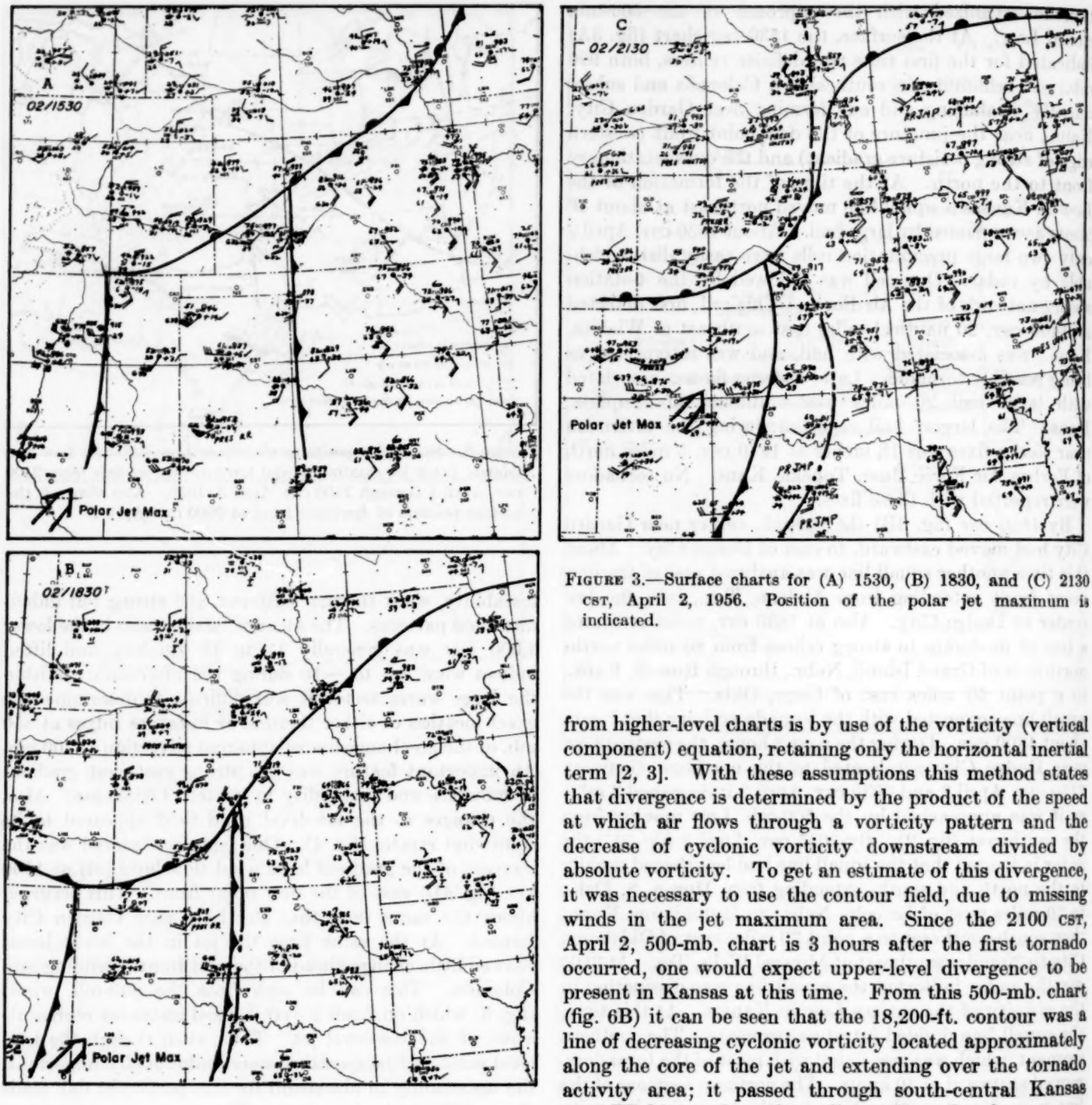


FIGURE 3.—Surface charts for (A) 1530, (B) 1830, and (C) 2130 CST, April 2, 1956. Position of the polar jet maximum is indicated.

as the 500-mb. center and remained to the southeast of the upper closed Low, moving northeastward at about 30 knots. The jet maximum was estimated to be 150 to 200 knots at an elevation near 25,000 feet at 2100 CST. Therefore, in Kansas and Oklahoma, events occurring near 500–400 mb. should have been representative of upper tropospheric conditions.

If a strong vertical motion field were moving into this area, it would be reasonable to expect divergence in the upper levels. One method of estimating this divergence from higher-level charts is by use of the vorticity (vertical component) equation, retaining only the horizontal inertial term [2, 3]. With these assumptions this method states that divergence is determined by the product of the speed at which air flows through a vorticity pattern and the decrease of cyclonic vorticity downstream divided by absolute vorticity. To get an estimate of this divergence, it was necessary to use the contour field, due to missing winds in the jet maximum area. Since the 2100 CST, April 2, 500-mb. chart is 3 hours after the first tornado occurred, one would expect upper-level divergence to be present in Kansas at this time. From this 500-mb. chart (fig. 6B) it can be seen that the 18,200-ft. contour was a line of decreasing cyclonic vorticity located approximately along the core of the jet and extending over the tornado activity area; it passed through south-central Kansas near Wichita and north to Concordia. On the assumption that this contour approximated a streamline and that wind speed decreased linearly from 150 knots at Childress, Tex., to 70 knots at Salina, Kans., the distribution of divergence in units of 10^{-5} sec^{-1} shown along this contour on the 2100 CST, April 2, 500-mb. chart (fig. 6B) was obtained. By comparing this with a streamline for the same area on the 0900 CST, April 2, 500-mb. chart (fig. 6A), where the speed decreased from 65 knots at Childress to 35 knots at Salina and change in direction was only 10°, it was found that the average divergence between Childress and Salina increased from less than 1×10^{-5}

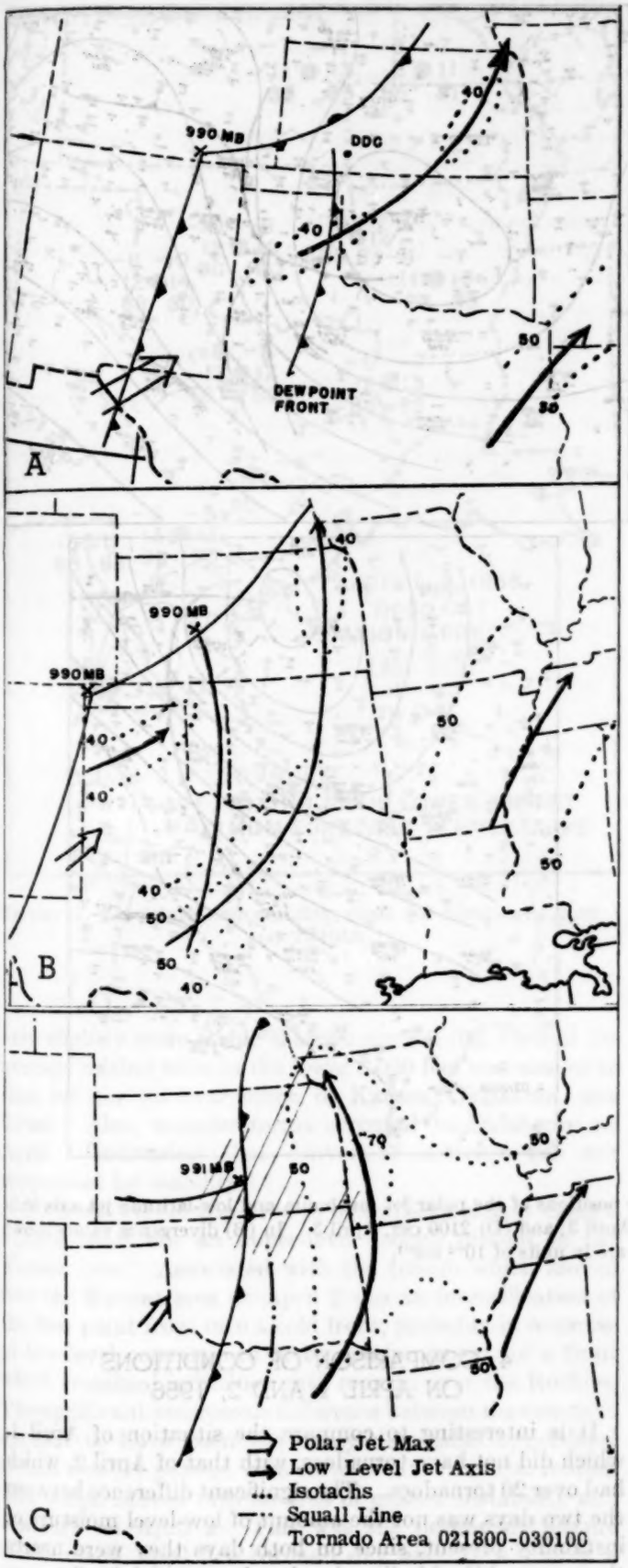


FIGURE 4.—Low-level wind field for (A) 0900, (B) 1500, and (C) 2100 CST, April 2, 1956.

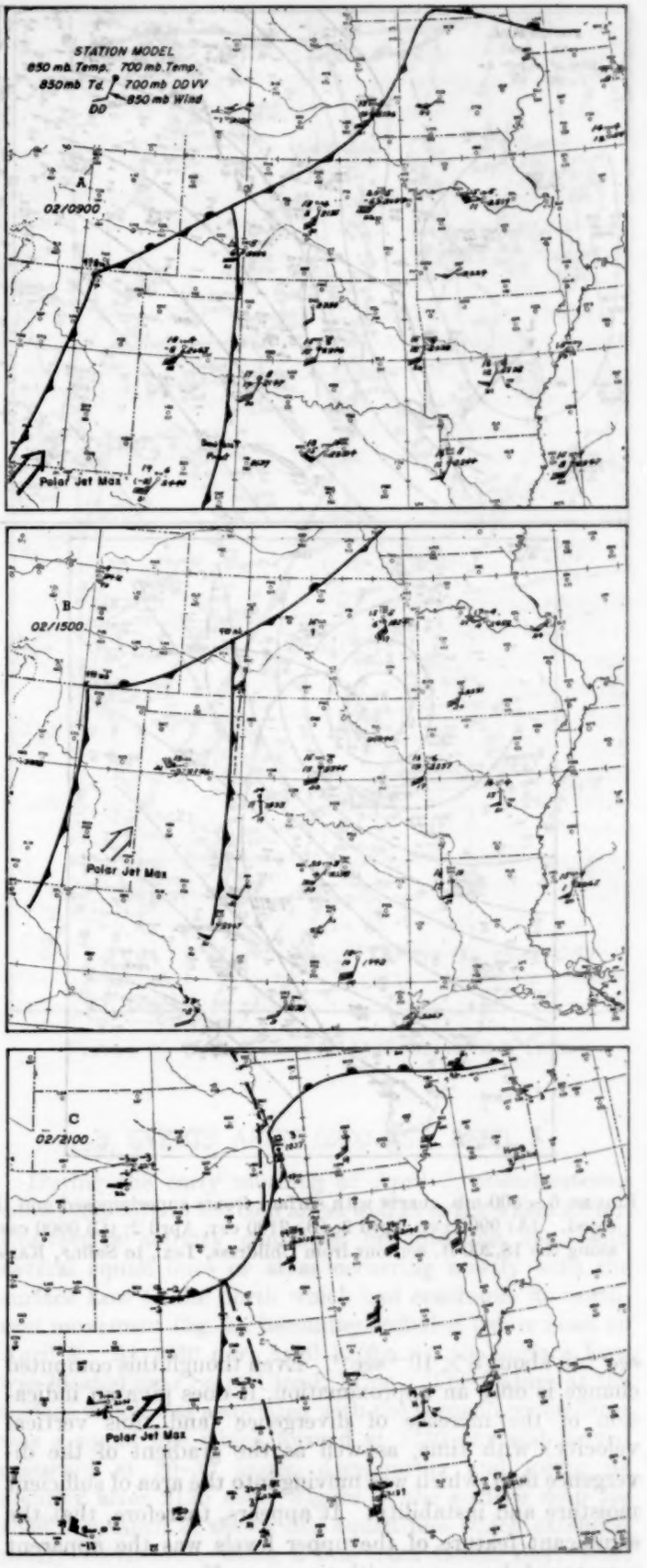


FIGURE 5.—850-mb. temperature, dewpoint, and wind and the 700-mb. temperature and wind, with the surface fronts and dewpoint front. (A) 0900, (B) 1500, and (C) 2100 CST, April 2, 1956.

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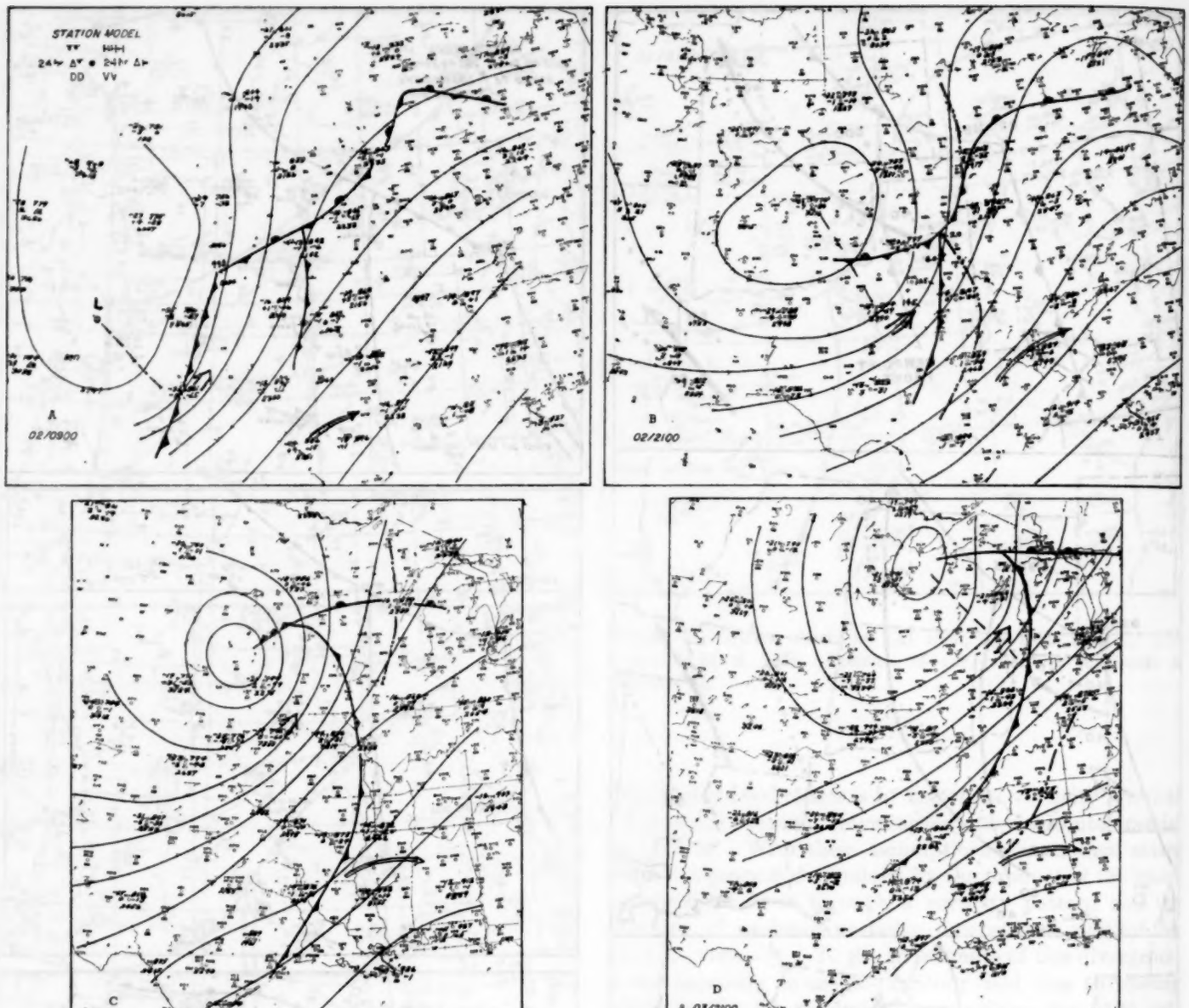

FIGURE 6.—500-mb. charts with surface fronts superimposed and the positions of the polar jet maximum and low-latitude jet axis indicated. (A) 0900 CST, April 2; (B) 2100 CST, April 2; (C) 0900 CST, April 3; and (D) 2100 CST, April 3. In (B) divergence values shown along the 18,200-ft. contour from Childress, Tex., to Salina, Kans., are in units of 10^{-5} sec^{-1}.

sec^{-1} to about 8×10^{-5} sec^{-1}. Even though this computed change is only an approximation, it does give an indication of the increase of divergence (and thus vertical velocity) with time, as well as the gradient of the divergence field, which was moving into the area of sufficient moisture and instability. It appears, therefore, that the significant feature of the upper levels was the apparent increase of divergence with time over Kansas.

4. COMPARISON OF CONDITIONS ON APRIL 1 AND 2, 1956

It is interesting to compare the situation of April 1, which did not have tornadoes, with that of April 2, which had over 20 tornadoes. The significant difference between the two days was not the amount of low-level moisture or instability present, since on both days they were nearly the same. Lifted indices for the afternoon of April 1 were

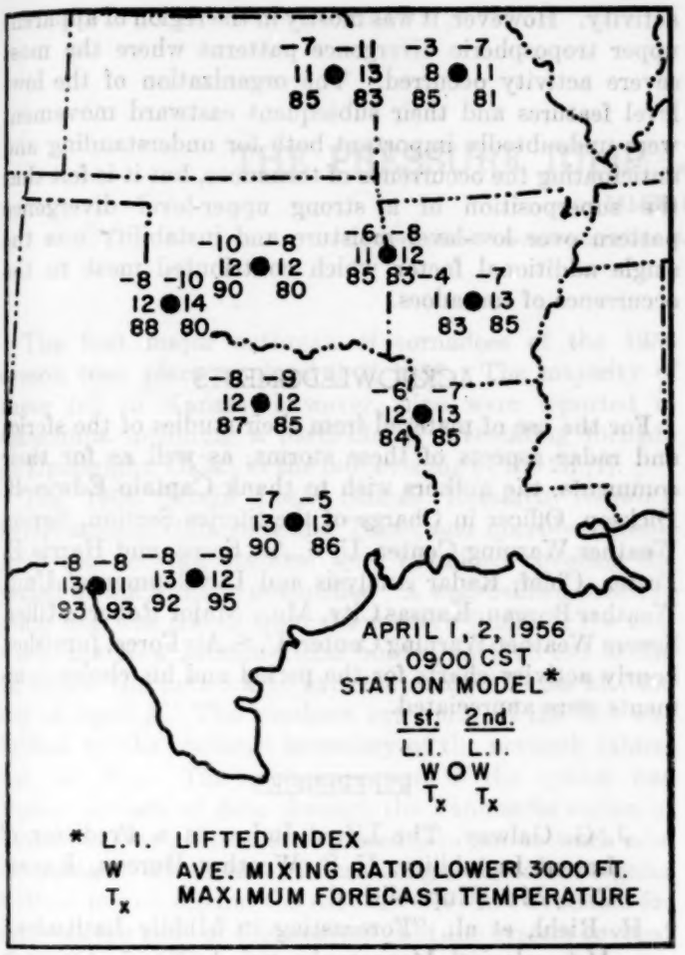

FIGURE 7.—Moisture and stability chart for 0900 CST, April 1 and 2, 1956.

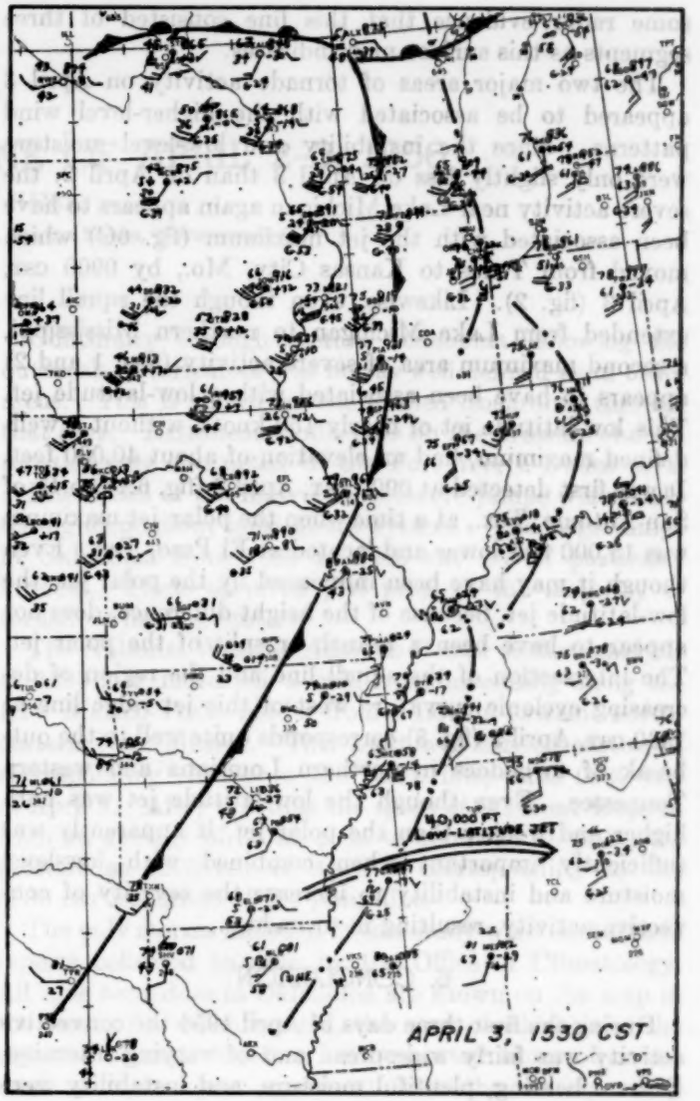

FIGURE 8.—Surface chart for 1530 CST, April 3, 1956.

only slightly more stable than on April 2 (fig. 7), and the average mixing ratio in the lower 3,000 feet was similar to that for the 2d over much of Kansas, Oklahoma, and Texas. Also, thunderstorms occurred in Oklahoma on April 1 indicating that convective activity was not suppressed by stability.

On April 1 there appeared to be neither a clearly defined surface front nor an upper-level trough present in the Kansas area. Associated with the trough which moved into the Kansas area on April 2 was an intensification of the dew point front into a cold front, probably in response to low-level convergence or by reinforcement by a front which remained indistinct until moving over the Rockies. The significant macroscale difference between the two days appears to have been the easily detectable upper-level trough and jet pattern with its associated vertical motion field which moved into an area of greater instability and moisture on April 2. This was the prominent feature which made April 2 a tornado day and April 1 only a thunderstorm day.

5. EVENTS AFTER 0200 CST, APRIL 3

During the early morning of April 3, thunderstorms continued both in the cold air as well as in the warm sector. Convective activity continued on into the day, with several squall lines or areas occurring mostly with the surface Low to the north which had continued its northeast movement (fig. 2), becoming occluded before noon on April 3. At 1530 CST, April 3 (fig. 8), the surface Low was located near Saint Cloud, Minn. The feature at the surface which was associated with the tornado occurrences was a squall line which formed at 1230 CST and moved eastward at 20–30 knots, decelerating and losing its identity after 2130 CST. Figure 8, the surface map for 1530 CST, April 3, shows this squall line which extended nearly north-south along a line from Green Bay, Wis., through Evansville, Ind., and Greenwood, Miss. There is

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some radar evidence that this line consisted of three segments as this surface map indicates.

The two major areas of tornado activity on April 3 appeared to be associated with the higher-level wind patterns. Since the instability and low-level moisture were only slightly less on April 3 than on April 2, the severe activity near Lake Michigan again appears to have been associated with the jet maximum (fig. 6C) which moved from Texas to Kansas City, Mo., by 0900 CST, April 3 (fig. 2). Likewise, even though the squall line extended from Lake Michigan to northern Mississippi, a second maximum area of severe activity (figs. 1 and 2) appears to have been associated with a low-latitude jet. This low-latitude jet of nearly 150 knots, without a well-defined maximum, had an elevation of about 40,000 feet. It was first detected at 0900 CST, April 2 (fig. 6A) north of San Antonio, Tex., at a time when the polar jet maximum was 15,000 feet lower and located at El Paso, Tex. Even though it may have been influenced by the polar jet, the low-latitude jet, because of the height difference, does not appear to have been a branch or split of the polar jet. The intersection of the squall line and the region of decreasing cyclonic curvature west of this jet ridge line at 1530 CST, April 3 (fig. 8) corresponds quite well to the outbreak of tornadoes in northern Louisiana and western Tennessee. Even though the low-latitude jet was both higher and weaker than the polar jet, it apparently was sufficiently important when combined with low-level moisture and instability to increase the severity of convective activity, resulting in tornadoes.

6. CONCLUSION

During the first three days of April 1956 the convective activity was fairly widespread and of varying intensity. Diurnal heating, plentiful moisture, and instability were undoubtedly all contributing factors to the convective activity. However, it was mostly in the region of apparent upper tropospheric divergence patterns where the most severe activity occurred. The organization of the low-level features and their subsequent eastward movement were undoubtedly important both for understanding and anticipating the occurrence of tornadoes, but it is felt that the superposition of a strong upper-level divergence pattern over low-level moisture and instability was the single additional factor which contributed most to the occurrence of tornadoes.

ACKNOWLEDGMENTS

For the use of material from their studies of the sferics and radar aspects of these storms, as well as for their comments, the authors wish to thank Captain Edwin B. Dickson, Officer in Charge of the Sferics Section, Severe Weather Warning Center, U. S. Air Force, and Harrie E. Foster, Chief, Radar Analysis and Developmental Unit, Weather Bureau, Kansas City, Mo. Major Robert Miller, Severe Weather Warning Center, U. S. Air Force, furnished hourly activity charts for the period and his choice comments were appreciated.

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THE PRESSURE JUMP LINE OF APRIL 2–3, 1956

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The first major outbreak of tornadoes of the 1956 season took place on April 2–3, 1956. The majority of these fell in Kansas; however, nine were reported in Oklahoma including a particularly devastating tornado at Drumright, Okla., in the late evening of the 2d [1].

The 1956 Severe Local Storms Research Network covers most of Oklahoma and Texas, and microbarograms from the network stations were examined covering the period of the tornado outbreaks. A well-defined pressure jump line was traced from the western limits of the network, the New Mexico-Texas border, at 1300 CST of the 2d across the network to extreme eastern Texas at 0300 CST of April 3. The southern extremity of the line was limited by the southern boundary of the network (about Lat. 30° N.). The northern extent of the system was limited by lack of data through the Panhandle region of Texas but was evident as it passed into the network area in western Oklahoma. Microbarograms from regular stations in and around the network were not available for study at the time of this analysis, but the system covered the entire network area and quite probably extended some distance beyond, particulary into both southern Texas and Kansas.

The average speed of the line over the network was approximately 40 m. p. h. The fastest movement during the period was 50 m. p. h. in the 4-hour interval 1300–1700 CST over western Texas.

Intensities of individual pressure jumps as read from the network barograms are plotted in figure 1 using established criteria and station model. To be considered a pressure jump, the pressure must rise at least 0.02 in. Hg at a rate of at least 0.01 in. per 2 minutes. The ratios of total pressure rise versus total time of rise are plotted to the left and the time of beginning of rise to the right of the station circle. Amounts of pressure rise have been entered in thousandths of an inch and total time of rise in minutes on the map. Any rise not meeting the criteria but apparently part of the system is indicated by "GR" (gradual rise) and stations for which no barograms are available are indicated by "M" (missing). One exception to the criteria was made at Carlsbad, N. Mex., where a rise of 0.06 in. in 20 minutes was entered. This report, and those from several other regular reporting stations, were obtained from teletypewriter circuit reports of pressure jumps.

Continuity through eastern Oklahoma following the outbreak of tornadoes was not as well defined as in other areas. This is shown by the dashed isochrones through that area. Extraneous influences on the pressure characteristics were also noted in the Fort Worth-Dallas area.

Intensities of the individual pressure jumps were fairly strong throughout most of the system. The large jumps in Oklahoma from 1800 to 2000 CST are of particular interest. These occurred just prior to the majority of tornadoes in that State.

The National Weather Analysis Center surface analysis at 1230 CST indicated a cold front extending along the New Mexico-Texas border from a Low in extreme northeastern New Mexico. This front was carried eastward, corresponding closely to the jump line, until 0030 CST of April 3. After this time the speed of the front dropped from an average of 30 m. p. h. to about 10 m. p. h., the position at 1230 CST of April 3 corresponding to the 0330 CST isochrone of the jump line.

The only storms included in this study were the tornado reports collected to date by the Office of Climatology. All nine tornadoes in Oklahoma are shown on the map in the form of a V-like symbol, the apex of which is at the reported tornado location. All reported times of occurrence were in close agreement with the corresponding isochrone of the pressure jump line, with tornadoes occurring either on the line or within a few minutes after the passage of the system. The tornado at Drumright, for example, struck at 2133 CST—the analysis shows the pressure jump line to have passed at approximately 2115 CST. Although two or three funnels fell just north of the network limits, they fit the extension of the respective isochrones, which, as mentioned earlier, probably extend northward into Kansas.

ACKNOWLEDGMENTS

The suggestions by Dr. Morris Tepper and Mr. William Hass were very helpful in the preparation of this paper.

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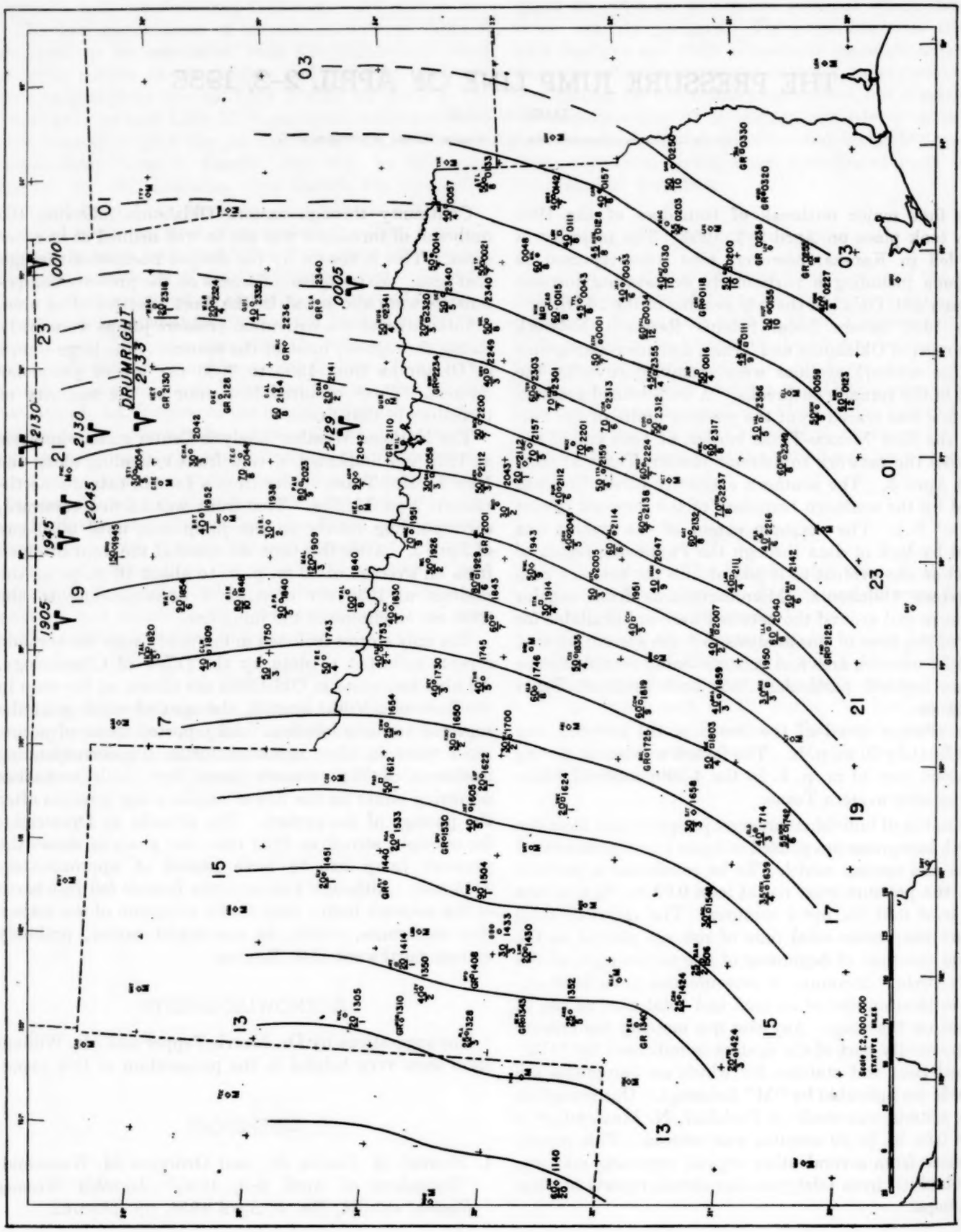

FIGURE 1.—Isochrones of pressure jump line of April 2–3, 1956. Ratio of total pressure rise in thousandths of an inch to total time of rise in minutes is plotted to left of each station circle, with time of beginning of rise to the right. GR=gradual rise; M=missing; V=tornado.

Weather Notes

RADAR ECHO AND ASSOCIATED TORNADO DAMAGE NEAR TOPEKA, KANS., APRIL 2, 1956

Late on April 2, 1956, a strange looking radar echo was observed on the scope at the Weather Bureau Office, Topeka, Kans. Until just before 2330 CST the echo had been fairly symmetrical. Then the center began to show an indentation and the southern end became pointed. The changes appeared to be due primarily to these portions of the echo becoming weaker. The northern portion continued strong. Other echoes are not included since only this one looked unusual.

Because of the way in which the shape was changing, it was decided to trace this echo. The sketch, made about 2335 CST, is reproduced in figure 1. As the 20-mile range did not provide good definition, the 50-mile range was used. Since the original tracing was made with wax pencil, the sharpness of the echo was not too well defined, particularly in the central and southern portions.

After this sketch was made and the report put on the RAWARC circuit, the echo was next noted about 2345 CST. There appeared to be a dark inverted U in the center almost due west of the station, and the point on the southern end was becoming more rounded. A sketch of the echo at this stage, although not made at the time, is included in an inset to figure 1. Shortly thereafter a power failure occurred, but the set was back in operation before midnight. By then the echo was becoming solid again, with the southern portion apparently dissipating and the northern section considerably the stronger.

No reports received at Topeka before or immediately after the passage of the echo attached any particular importance to it at that time, although a rather sharp pressure jump with wind gusts of 54 knots—not unusual for thunderstorms in this area—occurred at the station. The station was apparently on the eastern edge of the echo although there was almost continuous thunder from all quadrants. The weakening of the echo seemed substantiated by the light rainfall.

A later plotting of approximate tornado damage paths on the sketch (see fig. 1) showed enough relation to the echo to make it worth reporting here. Locations where time of tornado damage have been definitely ascertained are shown on the sketch. Overdeveloped mammatus or incipient funnels 7 or 8 miles south-southwest of the observation point and 4 or 5 miles to the east of any damage area were observed between 2335 and 2350 CST. No rotary motion could be detected in the mammatus which have been described as having an accordianlike pulsating movement and which reached close enough to the ground to obscure the beacon at Forbes Air Force Base while runway lights were plainly visible.—*G. E. Brokaw, WBO, Topeka, Kans.*

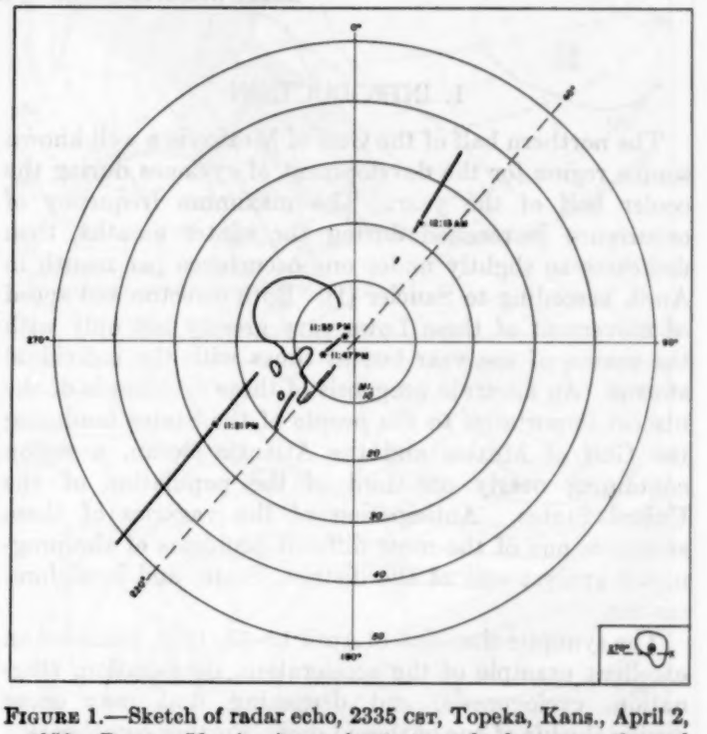

FIGURE 1.—Sketch of radar echo, 2335 CST, Topeka, Kans., April 2, 1956. Range: 50 mi. Approximate tornado damage paths and locations where time of damage is definitely known are shown. Inset.—Sketch of echo about 2345 CST. Range uncertain.

plotted to left of each station circle, with time of beginning of rise to the right. GR=gradual rise; M=missing; V=tornado.

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THE UNUSUAL MOVEMENT OF THE GULF OF MEXICO CYCLONE, APRIL 10–13, 1956

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1. INTRODUCTION

The northern half of the Gulf of Mexico is a well-known source region for the development of cyclones during the cooler half of the year. The maximum frequency of occurrence is reached during the winter months, then decreases to slightly under one occurrence per month in April, according to Saucier [1]. Both directon and speed of movement of these Lows vary greatly not only with the season of the year but at times with the individual storms. An accurate prognosis of these cyclones is of the utmost importance to the people of the States bordering the Gulf of Mexico and the Atlantic Ocean, a region containing nearly one-third of the population of the United States. Anticipation of the vagaries of these storms is one of the most difficult problems of the prognostic analyst and of the district, State, and local forecasters.

The synoptic situation of April 10–13, 1956, furnishes an excellent example of the acceleration, deceleration, stagnation, cyclogenesis, and deepening that may occur during the life of one of these Lows. Further complicating this situation was the development of a cold core Low during this period over the Carolinas. This storm was investigated because during its life along or near the east coast the actual track deviated considerably from the expected path. The resultant error in the forecast track was partially responsible for the over-forecasting of precipitation in the northeastern States. In this study a few factors associated with the erratic behavior of this storm, as well as a general comparison of prognostic techniques, and an actual comparison of the prognostic charts from the National Weather Analysis Center and the Joint Numerical Weather Prediction Unit are presented.

2. ANTECEDENT CONDITIONS, APRIL 7–9

A moderately intense cold front that had crossed the Pacific Ocean began moving onshore over the northwestern portion of the State of Washington by the morning of April 7, 1956. By the morning of April 8 a weak low pressure center had developed over portions of northwestern Wyoming and southeastern Montana. This Low had formed at the intersection of a moderate Pacific polar cold front and an old stationary front along the eastern slope of the Rockies. During this period of 24 hours the center of the cold air on the 1000–500-mb. thickness chart had a value near 17,400 ft., while the value along the shear line, which indicated the position of the cold front, was near 18,200 ft. At 500 mb. the winds on the back side of the associated trough indicated a rather rapid transport of cold air southward.

The surface low pressure center was located over the Texas Panhandle by early morning of April 9, having plunged southward along the eastern slope of the Rockies. In the same period the attendant cold front had been driven rapidly southward in conjunction with the continued advection of cold air aloft and the maritime polar front had crossed the southern borders of New Mexico and Arizona. To the north of the low center the occluded portion of the surface front was being dissipated almost as rapidly as it formed while the Low was plunging southward.

Generally the shear across the warm front until this time had remained moderate in intensity but by 1500 GMT of April 9, the gradient across the front was weakening and another shear zone was intensifying farther south. This developing shear was located along an old maritime polar front that had been lying more or less stationary in the Gulf of Mexico and eastward into the Caribbean and the Atlantic Ocean. The thickness gradient not only continued to be maintained to the rear of the cold front but intensified, so that the frontal classification was increased to strong.[1] Thus a change from moderate to strong intensity of the front occurred notwithstanding that it had been driven southward some 1,200 miles during the past 2 days. The frontal intensification resulted from two factors: first, a continued strong advection of cold air southward, and second, the gradual moderation of temperatures behind the front. The latter was indicated by a rise of nearly 600 ft. in the thickness value immediately to the rear of the front, and the former by the persistency of the 17,600-ft. height line around the center of the cold air as it moved southward.

Over the central and eastern portions of the United States prior to 1230 GMT April 9, there had been an intense

[1] At the National Weather Analysis Center the criterion used for the determination of the intensity of fronts is the shear across the front of the 1000–500-mb. thermal winds; a difference of 25–49 knots indicates a front of weak intensity, 50–79 knots, moderate, and 80 knots or greater, strong intensity.

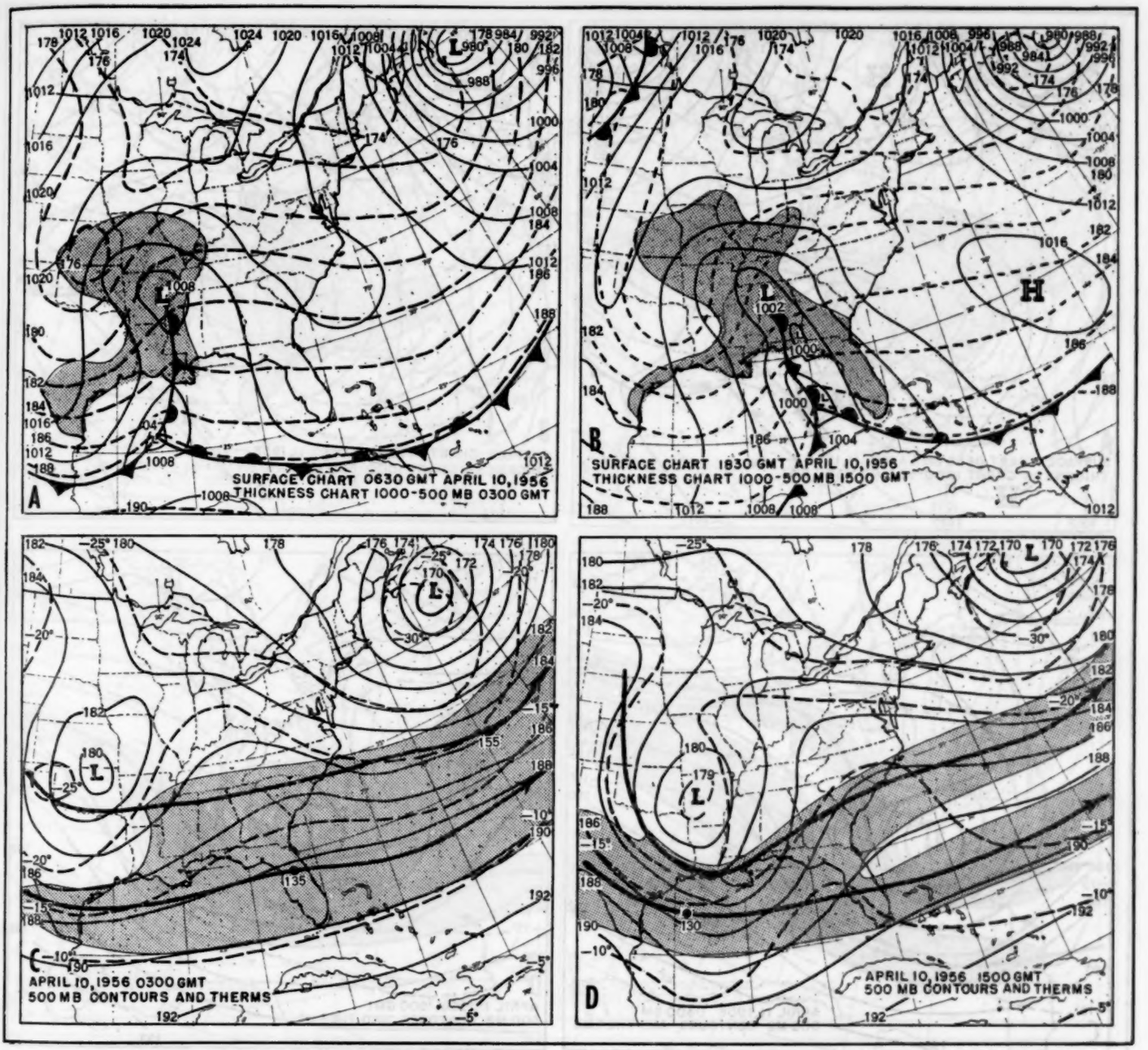
SURFACE CHART 0630 GMT APRIL 10, 1956
THICKNESS CHART 1000-500 MB 0300 GMT
A
SURFACE CHART 1830 GMT APRIL 10, 1956
THICKNESS CHART 1000-500 MB 1500 GMT
B
APRIL 10, 1956 0300 GMT
500 MB CONTOURS AND THERMS
C
APRIL 10, 1956 1500 GMT
500 MB CONTOURS AND THERMS
D

FIGURE 1.—Synoptic patterns for April 10, 1956. (A) 0630 GMT surface chart with 1000–500-mb. thickness for 0300 GMT indicated by dashed lines. Shading covers precipitation area during preceding 24-hour period. (B) 1830 GMT surface chart. (C) 0300 GMT, 500-mb. chart. Heavy arrowed lines indicate 200-mb. jet stream. Shading covers regions of 100-knot or higher wind speeds with position and value of maximum shown by numbers near jet stream. (D) 1500 GMT, 500-mb. chart.

low pressure center at the surface and aloft. But by the afternoon of April 9 it was moving off the east coast. A moderately intense anticyclone separated the two Lows early in the period but this High had gradually diminished, becoming a weak ridge as it moved northeastward between the two depressions.

3. SYNOPTIC FEATURES, APRIL 10–13

Late in the day on April 9 or early morning (GMT) of the 10th the maritime polar front coalesced with the old stationary front. This occurred either in the extreme southern portion of Texas or over the western Gulf of Mexico near the Texas coast. From the point of juncture, northward to the center of the Low, the cold front had rapidly assumed occluded characteristics. All signs of the northern warm front that earlier had been a segment of the original frontal system associated with the Low had dissipated.

The 0300 GMT 500-mb. chart (fig. 1C) of April 10 presented a trough, ridge, trough, ridge, and trough pattern

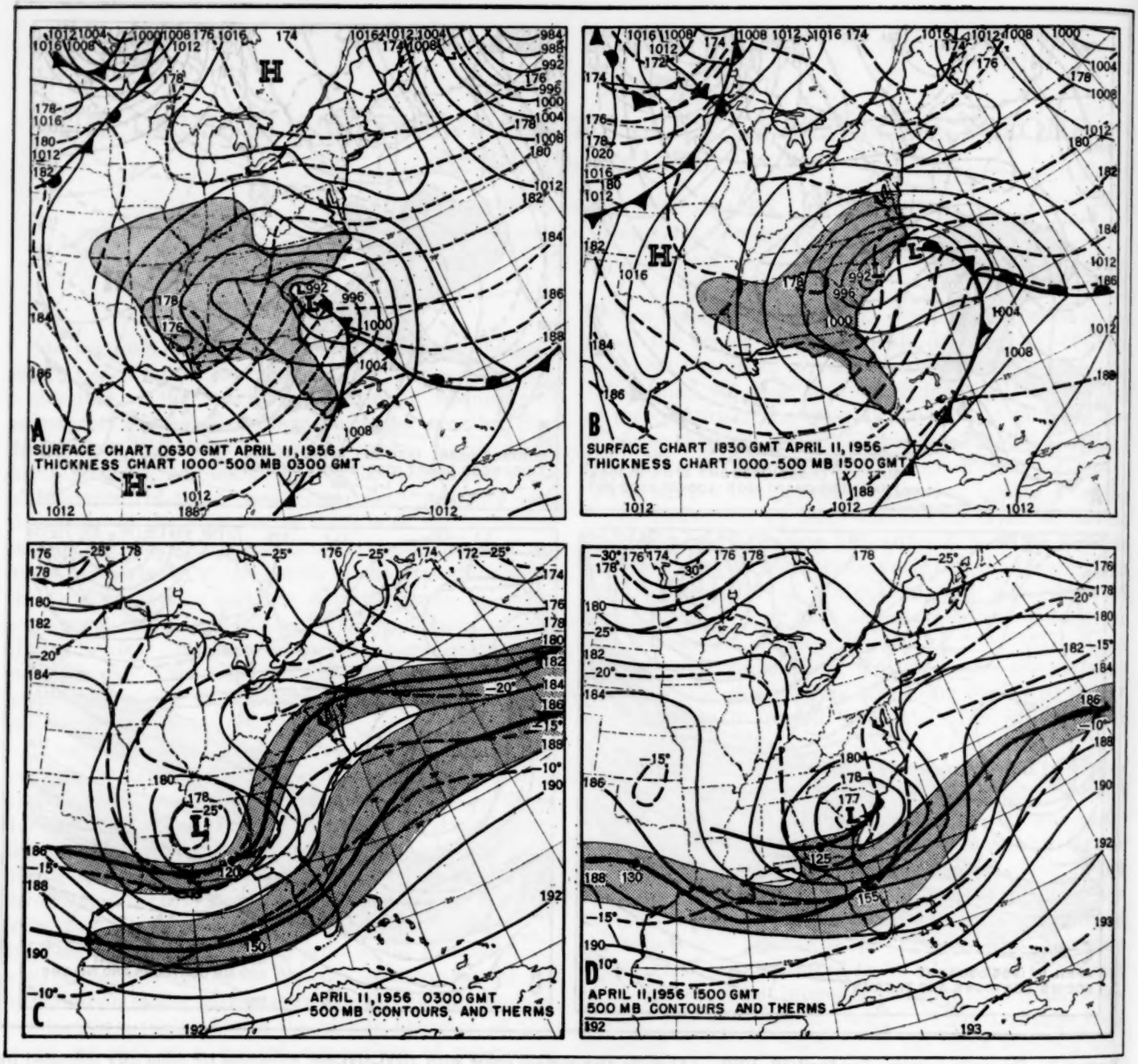
A
SURFACE CHART 0630 GMT APRIL 11, 1956
THICKNESS CHART 1000-500 MB 0300 GMT
B
SURFACE CHART 1830 GMT APRIL 11, 1956
THICKNESS CHART 1000-500 MB 1500 GMT
C
APRIL 11, 1956 0300 GMT
500 MB CONTOURS AND THERMS
D
APRIL 11, 1956 1500 GMT
500 MB CONTOURS AND THERMS

FIGURE 2.—Synoptic patterns for April 11, 1956.

between the 25th and 45th parallels from 60° to 130° W. All troughs had at least one closed height contour about the central area and the central height values within these closed contours rose progressively westward. Both ridge areas were rather weak with the westernmost one being the more pronounced of the two. The upper low center with which we are concerned (fig. 1C) was located near Tulsa, Okla., with the trough extending south-southwestward. An area of cyclonic vorticity was indicated south of this center on both the 500-mb. and the 1000–500-mb. thickness charts (fig. 1A and 1C). At the same time an area of confluence was located near the juncture of the four States of Arizona, New Mexico, Utah, and Colorado. The confluence area remained rather well defined during the next 24 hours and this, along with the intensifying gradient, aided in producing westerly winds of high speed, south of the upper low center.

During the next two days the winds at 500 mb. ranged from 60 to 120 knots with numerous observations indicating westerly winds of 70 to 80 knots. Much less pronounced contour gradients were prevalent during this period to the east and west of the low center (figs. 1C,

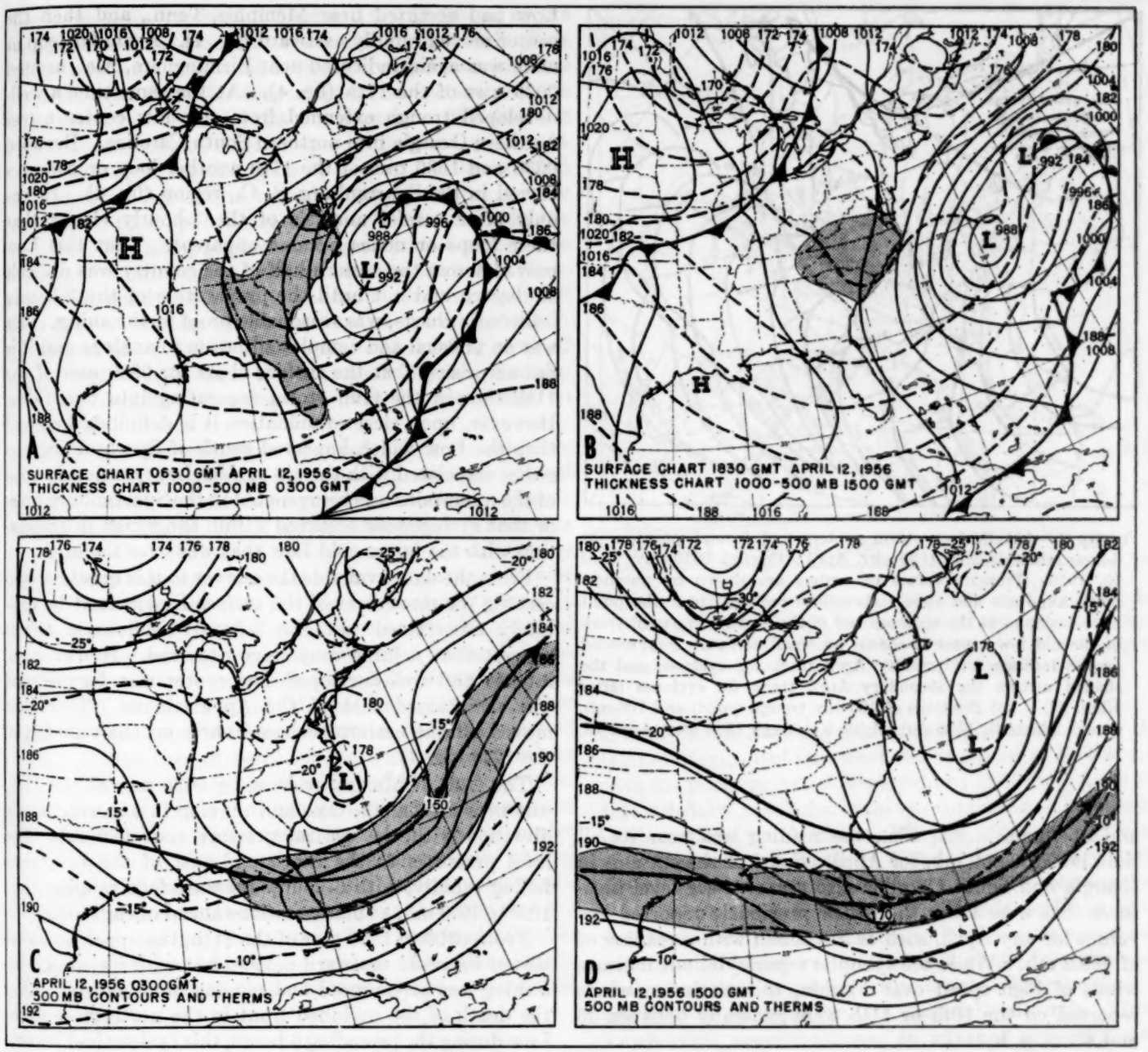
A
SURFACE CHART 0630 GMT APRIL 12, 1956
THICKNESS CHART 1000-500 MB 0300 GMT
B
SURFACE CHART 1830 GMT APRIL 12, 1956
THICKNESS CHART 1000-500 MB 1500 GMT
C
APRIL 12, 1956 0300 GMT
500 MB CONTOURS AND THERMS
D
APRIL 12, 1956 1500 GMT
500 MB CONTOURS AND THERMS

FIGURE 3.—Synoptic patterns for April 12, 1956.

1D, 2C, 2D, 3C, 3D) with the prevailing winds less than one-half the speed of the westerly flow. On the surface chart for 1230 GMT of the 10th, deepening had occurred at the point of occlusion, now over the central portion of the Gulf of Mexico, and the central pressure was 998 mb. (fig. 4). The front extending north of this center continued to be maintained and was active in producing heavy showers and thunderstorms as it moved eastward. By 1500 GMT of the 10th (fig. 1D), the 500-mb. center was near Little Rock, Ark. Slight intensification had occurred at the center of the upper Low and the attending trough was moving to the east ahead of this center. The upper ridge to the east of the Low showed a slight tendency to strengthen and to build northward.

Within the next 12 hours, ending at 0030 GMT of the 11th, the central sea level pressure of the cyclone lowered to 994 mb. (fig. 4) and was located approximately 80 nautical miles north of Tampa, Fla. That it had become an unusually intense storm can best be realized by the comparison of the existing sea level pressure records for April [19] with the barometric values that occurred during this storm. At Key West, Fla., a low reading of 1001.0 mb. was 2.3 mb. lower than the previous record; at Tampa, Fla., a reading of 999.3 mb. was 2.0 mb. lower;

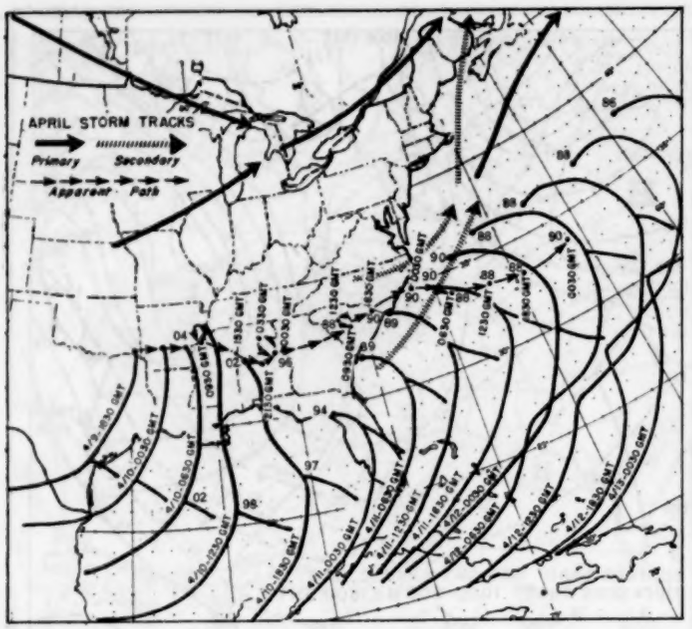

FIGURE 4.—(A) Surface storm centers and frontal positions at 6-hour intervals from 1830 GMT, April 9 through 0030 GMT, April 13, 1956. Pressure values of centers are shown by numbers (with hundreds and thousands values omitted) near the point of occlusion or at the northern end of the front. Apparent track of the old low center is shown by small arrows. Heavy solid arrows indicate the primary April track for cyclones and the shaded arrows the secondary April track for cyclones (after Klein [8]). (B) Positions of 500-mb. trough (solid) and 700-mb. trough (dashed), 1500 GMT, April 9 through 1500 GMT, April 12, 1956.

and at Apalachicola, Fla., the reading was near its all time low of 997.6 mb. for April. Some of the stations in Georgia and South Carolina also reported sea level pressures that were lower than their previously reported low values for any April, such as Savannah with a reading of of 989.2 mb. While the synoptic reports did not indicate winds of high speed over Florida, the maximum winds reported on the 10th or 11th were generally between 35 and 40 m. p. h.

The 0300 GMT 500-mb. chart of the 11th (fig. 2C) failed to indicate further building of the ridge ahead of the Low. In fact, a reversal of that trend appeared to be in progress as the ridge continued its eastward motion. During this time the 500-mb. Low was intensifying and the speed of its eastward motion was increasing. The trough, with its easternmost position over the Atlantic Ocean, by now had been carried far ahead of the low center.

By 0030 GMT of the 11th (fig. 4), the front which had connected the two surface pressure centers had apparently dissipated although a well defined trough remained. This old Low had continued in a general eastward direction but its movements were unusual and erratic as it traversed the area from Memphis, Tenn., to Spartanburg, S. C. Between 0630 and 1830 GMT of the 10th, the 3-hourly surface charts indicated that a loop or node in the track of the Low had occurred near Memphis, Tenn., and then the center moved rapidly eastward (fig. 4). A similar loop or node was again indicated near Birmingham, Ala., around 0030 GMT of the 11th (fig. 4). At the same time a well-developed trough extended from this low center across northern Georgia into northern South Carolina. Between 0630 and 1530 GMT of the 11th another loop or node occurred in the Spartanburg, S. C., region (fig. 4). It was only after careful analysis of the 3-hourly charts that these loops or nodes became apparent. That this Low moved across the eastern half of the country was difficult to discern and not until the preparation of the 3-hourly isallobaric charts, was reasonable proof forthcoming. This was an unusual and complex situation to analyze and it is not surprising that the surface chart for 0930 GMT of the 11th showed the Gulf storm separating into two Lows. However, upon close examination it is definitely believed that the Low which appeared south of Spartanburg was either associated with the old surface Low previously west of the mountains and rejuvenated in the Spartanburg area, or that cyclogenesis occurred within the region in association with the upper cold Low that was over the area.

From the data available the answer to this question concerning the movement of the surface Low cannot be definitely ascertained but the 3-hourly isallobaric charts suggest that a jump may have occurred. However, an intense and well-developed low center was formed and was maintained east of the Appalachians. This Low moved off the eastern seaboard early on the morning of the 12th (fig. 4).

The Gulf of Mexico cyclone, by 0630 GMT of the 11th, was near Savannah, Ga., and moving in a northeasterly direction with the central pressure near 989 mb. Sea level pressures to the north and east of the Low were falling rapidly, with 6-hourly pressure falls ranging from 10.0 to 15.0 mb. at many stations ahead of the storm.

From 0300 to 1500 GMT of the 11th, the upper Low continued its rapid eastward motion but with its trough becoming less pronounced and moving more slowly. After the death of the occluded front in the northern-centered Low during the preceding 6 hours, this cyclone had become a well-developed cold-core Low with a pronounced and descending tropopause center. It was during this period that the upper center of the Low apparently reached its maximum strength with a height of less than 17,700 ft. at the 500-mb. level. Concurrently the west winds at this level attained the maximum reported velocity of 120 knots. The distance between the surface position of the Gulf of Mexico storm and the location of the cold-core center had decreased approximately 50 percent during the past 24 hours.

By 1230 GMT of the 11th (fig. 4) there had been a definite alteration in the path of the surface Low for it was now moving in an east-northeast direction. The Low continued to swing to a more easterly direction during the next 12 hours. But the central value remained practically unchanged during this time with near record

pressures being reported. During April 11 (GMT), as the storm skirted the coast line south of Hatteras, high winds predominated. The intense pressure gradient in this area resulted from the deepening of the cyclone and the northward movement of the storm center. Winds along the Carolina coasts reached speeds of 75 m. p. h. At Charleston, during this period, a new maximum wind velocity for April was recorded [2], with a 1-minute average of 65 m. p. h. from an easterly direction. In the Norfolk, Va., area, gale winds began at 1345 GMT of the 11th and continued until 0330 GMT the next day [3], a period of nearly 14 hours. The maximum average wind speed for a 1-minute period was 62 m. p. h. from a northerly direction. Considerable damage and flooding resulted from high winds and tides in and around Norfolk. Further details concerning this will be mentioned in section 8.

As the old low center now associated with the cold-core cyclone moved off the east coast it was partially depressed southeastward by the strong northeast flow. Also it appears that the southeast movement may have been due in part to the tendency of two cyclones of equal intensity to revolve around each other in a counterclockwise sense [4]. However, in this double-centered storm it appears that only partial revolution occurred. The old center then gradually recurved toward the east and northeast maintaining a relatively constant distance to the southwest of the Gulf of Mexico Low. In the upper air the rapid eastward movement of the cyclone continued through 0300 GMT of April 12 (fig. 3C) with indications of a slight decrease in the intensity of the central value. However this fact is not definite as the center was then over the ocean. The trough ahead of the low center continued to decelerate and was assuming a more normal position, while a new trough was developing in the southwestern quadrant. It also appeared at this time that the Low was elongating since a new center was in the process of formation ahead of the old center. By 1500 GMT the elliptical appearance had become more pronounced (fig. 3D).

4. THREE-HOURLY PRESSURE CHANGE

The 3-hourly pressure change tendencies during the formative stage of the Gulf of Mexico cyclone indicated an isallobaric field similar to that normally expected in a cyclogenetic area, while the original storm center in Arkansas had 3-hourly falls of from 1 to 2 mb.[2] At 0630 GMT April 10 katallobaric tendencies of between 3 and 4 mb. appeared in the Memphis area and similar values covering a slightly larger area were present near 26° N., 91° W. (See fig. 5 for path of movement.) By 1230 GMT the northern katallobaric area had moved to the vicinity of Tupelo, Miss., with the falls less intense in that region than in the area southeast of New Orleans where falls had increased to values of 5 and 6 mb. near the center. The

[2] All 3-hourly values mentioned have had the diurnal corrections applied.

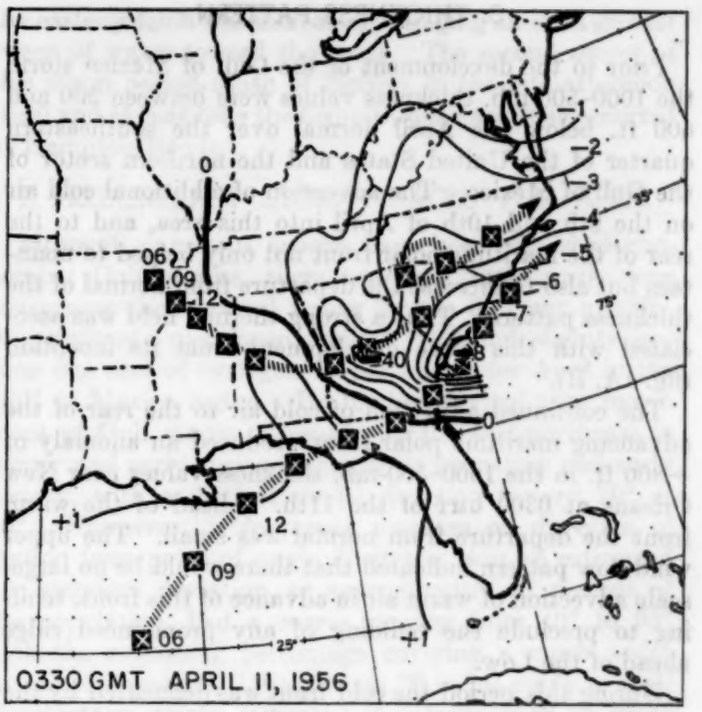

FIGURE 5.—Three-hour isallobars (labeled in whole millibars) for 0330 GMT, April 11, 1956, corrected for diurnal pressure changes. Shaded lines indicate path of katallobaric centers, 3-hour positions indicated, beginning with 0630 GMT, April 10, 1956.

area of the katallobaric field of the deepening Low in the Gulf of Mexico had increased and appeared to be merging with the northern katallobaric field by 1830 GMT, April 10. But a definite katallobaric trough continued to be present in the region from Meridian, Miss. to Montgomery, Ala., with the main fall center of 5 and 6 mb. in the vicinity of Tallahassee, Fla. However, by the 0030 GMT chart of the 11th (fig. 5) the 3-hourly katallobaric field had separated into two distinct centers. The fall area associated with the Gulf Low was located east of the Georgia coast with central falls greater than 6 mb. while the second center, near Phenix City, Ala., had falls of 4 mb. These katallobaric areas continued to advance east-northeastward during the next few charts with the central falls approaching 8 to 10 mb. in a 3-hourly period.

Between the hours of 0630 GMT and 1530 GMT of the 11th the katallobaric field associated with the Gulf of Mexico storm advanced steadily toward Cape Hatteras. During the same time the field associated with the old Low moved from Columbia, S. C., to near Charlotte, N. C. At 0930 GMT the katallobaric center was approximately 30 nautical miles southeast of Charlotte, N. C.; and then during the next 5 hours this center apparently circled that city within a radius of 30 nautical miles. It is opined that it was during this period that the old surface Low either jumped or was rejuvenated east of the mountains and that this katallobaric loop or node reflected this eastward jump or rejuvenation of the surface portion of the cold-core Low.

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5. THICKNESS PATTERN

Prior to the development of the Gulf of Mexico storm the 1000–500-mb. thickness values were between 200 and 600 ft. below the April normal over the southeastern quarter of the United States and the northern sector of the Gulf of Mexico. The advection of additional cold air on the 9th and 10th of April into this area, and to the rear of the maritime polar front not only helped to maintain but also to increase the departure from normal of the thickness pattern. Thus a strong thermal field was associated with this wave development from its inception (fig. 1A, B).

The continued advection of cold air to the rear of the advancing maritime polar front produced an anomaly of −800 ft. in the 1000–500-mb. thickness values near New Orleans at 0300 GMT of the 11th. Ahead of the warm front the departure from normal was small. The upper wind flow pattern indicated that there would be no large-scale advection of warm air in advance of this front, tending to preclude the building of any pronounced ridge ahead of the Low.

During this period the cold front was delineated by the 18,800 ft. thickness line (fig. 2A, B) while the thickness value encircling the center of the cold air ranged from 17,600 to 17,800 ft. with the distance between the two extremes approximately 600 miles. Such a gradient would indicate thermal winds with an average velocity of 90 knots and a speed near 100 knots along the front. There being little or no thickness gradient south of the front, a thermal shear in excess of 80 knots would ensue. This would require the cold front to be classified as strong.

6. TROPOPAUSE

During the period from the 9th to the 12th of April, a field of below normal tropopause heights to the west of the original surface low center reached a minimum almost vertically above the low centers at 700, 500, 300, and 200 mb. At 0300 GMT of the 10th, this low tropopause was centered in the vicinity of Wichita, Kans., and by 1500 GMT of the 10th had moved to near Springfield, Mo., with the height dropping to 25,000 ft. On the 11th of April at 0300 GMT the center was near Birmingham, Ala., the central height value continuing near 25,000 ft. But by 1500 GMT, the tropopause center had moved eastward to near Charleston, S. C., with the height lowering to 23,000 ft. or a pressure of 416 mb. and a temperature of −37° C. Earlier, Montgomery, Ala. confirmed this low tropopause with a pressure of 350 mb. and a temperature of −42° C. That 23,000 ft. was an extremely low tropopause for Charleston is indicated by a comparison with available tropopause data for Norfolk, Va., which, being north of Charleston, would be expected to experience low tropopauses more frequently than Charleston. At Norfolk over 95 percent of tropopause heights are above 27,000 ft. during the months of March, April, and May [5]. It was also noted that a 500-mb. temperature equal to or lower than the −23° C. observed at 1500 GMT, April 11 at Charleston, has been observed only 15 percent of the time at Norfolk [5] where the 500-mb. temperature is normally lower than at Charleston.

7. PRECIPITATION

Storms that develop in the Gulf of Mexico are one of the main sources of precipitation for the southern States and often produce some of the larger rainfall or snowfall accumulations in the eastern seaboard States. It is for this reason that the prognoses of movement and location of Gulf of Mexico storms are so important to the eastern residents of our nation.

One can easily see by a rapid check of the precipitation totals that the production of precipitation by this storm was similar to most other Gulf of Mexico cyclones. The 24-hour rainfall totals ending at 1230 GMT, April 10, indicate widespread precipitation over the middle and lower Mississippi Valley, the lower Missouri Valley, the Arkansas Valley, and a portion of the Red River Valley with the larger totals having occurred in the western portion of the Gulf Coastal Plains (see figs. 1, 2, and 3, A and B). In this Gulf Coast area, 24-hour totals were generally from 1 to 2 inches with amounts locally reaching 5.00 inches at Cadiz, Tex., and 3.00 inches at Ingleside, Tex. A few totals in excess of 1 inch were also recorded in the Ozark Plateau area.

By the 1230 GMT chart of April 11, the Gulf of Mexico storm center had become fully developed and had swung northeastward, crossing the northern portion of the Florida Peninsula. The attending rainfall pattern also continued to be widespread as it advanced eastward. During the 24 hours previous to 1230 GMT of the 11th precipitation had occurred over practically all of the southeastern quarter of the United States. East of the Appalachians the northern edge of the precipitation area was sharply defined in southern Virginia. A few of the larger rainfall totals were: Columbia, S. C., 3.64 inches; Charleston, S. C., 2.21 inches; Lincolnton, Ga., 2.50 inches; and City Office at Miami, Fla., 2.52 inches. It was this storm that brought temporary relief from a serious drought condition in Florida and eased the treacherous forest and brush-fire hazards. During the 57 days preceding this storm the total precipitation at Miami, Fla., was only 0.26 inch and the rainfall had occurred at widely spaced intervals.

The Gulf of Mexico storm center continued its eastward movement and by 1230 GMT April 12 was located 600 nautical miles east of Norfolk, Va. The related cold-core Low that had developed over the southern Appalachians the preceding day brought heavy rains as it moved eastward in the wake of the Gulf storm. In the 24 hours ending at 1230 GMT of the 12th precipitation had occurred over the southern Coastal Plains and the southern Appalachians with totals in excess of 1 inch reported in North

Carolina and southeastern Virginia. Thus with the eastward movement of these centers the threat of heavy rains from Virginia northward had ended. The demarcation line between measurable precipitation and no precipitation had remained sharply defined along the northern border of Virginia. Washington, D. C., reported only a trace of precipitation from the double-centered storm.

According to climatological records the accumulated rainfall totals from the storm ranged from 1 to 12 inches in North Carolina and locally snowfall totals in the North Carolina mountains reached a depth of 11 to 12 inches [6].

8. EFFECTS OF THE STORM

Beneficial results and destructive effects occurred from this storm. In southern Florida it was the first productive precipitation for nearly two months, thus reducing the prevalent fire hazards and furnishing much needed moisture. At the same time it produced local wind damage. Miami reported an apparent tornado in nearby areas shortly after 2330 GMT of the 10th, but the damage reported from later investigation was classified as wind damage. Another tornado was reported in the vicinity of St. Simon Island off the southeastern Georgia coast at 0430 GMT of the 11th. This was later classified as a waterspout. Along the Florida coast some damage was done to barges and small boats. Minor damage prevailed along much of the coastal sections north of Florida due to high winds and tides. However, the bulk of the damage of this storm occurred from Hatteras northward with the greatest havoc occurring in and around Norfolk, Va.

In the Norfolk area, widespread high tides were reported. Hampton Roads experienced the highest tides since 1936, including hurricane tides, and the highest tides of this century, excluding hurricane tides. Several city blocks in Norfolk were inundated and the water reached a depth of several feet in a few of the streets. Ocean-going transports and naval vessels were washed ashore due to the gale winds and high tides.

This storm pattern presented a combination of several features favorable for the development of high tides. The nearness of the two centers, their extreme intensities, and their paths apparently furnished essential ingredients for producing these extremely high tides. From 1230 GMT of the 11th to 0030 GMT of the 12th, the Gulf storm moved slightly north of east, passing just south of the North Carolina Capes, with the central pressure of the cyclone remaining nearly constant. Moving along this track it allowed a 10- to 15-mb. pressure differential to be maintained across the 2° of latitude from the low center to Norfolk, Va. This extremely strong pressure gradient produced gale winds from the east and north over Norfolk and vicinity that prevailed for nearly 14 hours. As the Gulf Low moved off the coast, the regenerated old cyclone was approaching the Norfolk area and with both centers of this April storm of approximately equal intensity there was no let up in the winds. In fact, the easterly fetch was increasing, bringing an even greater sweep of water toward the coast. The second center of this storm passed south of Norfolk in the late afternoon (EST) and at that time the highest tides since 1936 occurred at Hampton Roads.

9. PREDOMINANT STORM TRACKS FOR APRIL

Although numerous articles have been published concerning Gulf storms, there has been little work done concerning their normal tracks for the different months. As previously mentioned Saucier [1] found slightly less than one case of cyclogenesis per month for April in the Gulf of Mexico region. He further advised that movement of Gulf storms is usually to the east-northeast in winter and early spring during their formation and early history, with a distinct modal direction toward 70° or 80°. However, his frequency diagram on direction of motion from point of origin illustrates that an estimated one standard deviation, or approximately 67 percent of the population, had a course ranging from 40° to 95° with the remaining percentage covering a much wider spread of directions. Weightman [7] in his study of Gulf Coast storm tracks indicated the April track as being from the Mississippi Coast east-northeastward to near Wilmington, N. C., and thence north-northeastward paralleling the Atlantic Coast and moving into southern Maine. According to Klein [8] in a recent study of storm tracks the April frequency was not sufficient in the Gulf of Mexico area to arrive at any definite conclusions as to a principal track; he therefore omitted it from his chart. However, he prepared principal tracks of April cyclones moving off the east coast of the United States (his Chart 4). A secondary storm track along the North Carolina-Virginia border and another off the Carolina coast converge northeast of Cape Hatteras into a primary track beginning near 39° N., 70° W., then swinging slightly east of northeast. This takes the storms on a course about 100 miles south of Nova Scotia and Newfoundland. Klein further indicates a secondary track that branches northward from a point where the previously mentioned primary path begins. This secondary path extends northward over New Brunswick, Canada. It can easily be seen from figure 4 that the course of this Gulf of Mexico storm was considerably south of the principal east coast tracks.

The unusual southerly track of this storm can best be explained by the mean charts for the month and also by the 5-day mean charts prepared by the Extended Forecast Section. One of the most striking features of the charts of 5-day mean 700-mb. height departure from normal was the continued development of a blocking ridge (see fig. 6 of the preceding article by Dunn [9]), prior to and during the period now under study. During the period April 4–8, there was a positive anomaly of 330 feet near 70° N., 60° W. Moving slowly southward during the next 5-day period the positive anomaly was near 65° N., 57° W. or just east of the southern portion of Baffin Island. Curving

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anticyclonically, it was over southern Baffin Island during the period April 11–15, with the mean anomaly near +610 feet. For a complete trajectory of the 5-day mean positive anomaly, see figure 7 in the preceding article by Dunn [9]. During the period April 4–8 there was a negative anomaly of −410 ft. near 40° N., 41° W. This anomaly center had a mean value of −500 ft. by the middle of the April 7–11 period and was near 43° N., 51° W. By the middle of the 5-day period April 11–15 it was still located at 43° N., 51° W. with a mean value of −420 feet. Thus there was a total difference of over 1000 feet between the anomaly centers. This strong block caused the westerlies to be displaced farther south than normal for April and thus the storms during this period were deflected south of the normal April track.

10. APPLICATION OF PROGNOSTIC TECHNIQUES

Several objective, or semi-objective techniques for forecasting cyclone movement were reapplied in this investigation for comparison of results with the observed positions of the storm and the prognostic positions issued by the Joint Numerical Weather Prediction Unit (JNWP) and the National Weather Analysis Center (NWAC). Several factors made reapplication of the various techniques desirable: 1. It was not known which of the techniques the NWAC forecasters may have used in the initial preparation of their prognoses. 2. In research preparatory to this study it was necessary to make several large-scale revisions of frontal positions, central positions of the Lows, intensity of the Lows, and the tracks of the two Lows on the surface charts. 3. Similar revisions were necessary on the upper air charts. On many points this need for reanalysis became apparent only in the light of later data or the preparation of auxiliary charts used in this study and was not easily discernible at the time of the original analysis. Thus, it should be understood that these comparisons of the objective techniques are applied to the corrected or revised analyses and in that light may show a more comparable agreement with the actual happenings in this storm.

The surface prognostic techniques were applied on only the 1830 GMT chart of April 10 and the 0630 GMT chart of April 11 (figs. 1B and 2B). These two surface charts, with times corresponding to the charts upon which the NWAC 30-hour prognoses are based, were considered to be among the most critical in deciding the future path of this storm. This was especially true at 0630 GMT of April 11 for a continued northward or northeastward movement would have brought widespread rains north of Virginia along the eastern seaboard. Therefore, one of the prime reasons for making these computations was to determine if these objective techniques would have indicated the south-of-normal track that occurred with the surface Low and also the rapid eastward movement of the 500-mb. trough. An easy comparison of the results from the various techniques depicting the distance and direction that the prognostic centers were from the actual Low centers can be observed on the polar coordinate graphs in figure 6. These charts also contain the positions of the various prognoses of JNWP and NWAC.

On the surface charts the following techniques were investigated and their results were as indicated:

1. The Palmer method [11] when applied to the 1830 GMT chart indicated a track some 8° south of the observed route. On the 0630 GMT chart, the calculated direction was 6° north of the actual position. The Palmer technique does not give a forecast track nor the speed of movement, but rather "the line on which it will be found 30 hours later, regardless of the path it may follow or the distance it may travel during the period."

2. The Bowie and Weightman [12] method was also applied to the same two charts with these results: On the 1830 GMT map it gave a course some 28° south of the observed track and a movement which was much too slow. The 0630 GMT chart indicated the direction of the track as 4° too far to the north and the distance of the expected position was nearly 100 nautical miles too far east. It would be well to mention that in the summation of data for April, Bowie and Weightman had only one storm in the two 5° areas that were applicable for the 1830 GMT position.

3. The "normal" or climatological averages by Hering-Mount [13] were prepared for a period from November 1 through March 31. However, on examination of their table it was of interest to note that the highest speed indicated for the movements of Category IV Cyclones[1] occurred during the period of January 16–31. By pairing off the period adjacent to this date and continuing with other consecutive pairs, it was noted that the bimonthly period of November 1–15 could be paired with the period for April 1–15, and so an estimation of 21 m. p. h. was adopted. Using this assumed speed and the predetermined course of the "normal" technique, the path and distance obtained from the 1830 GMT chart was 9° south of the true path and 230 nautical miles from the observed center. A forecast from the 0630 GMT chart by this same technique indicated a course which was 9° to the north of the actual track and a position 220 nautical miles from the observed center. Both estimated movements were west of the actual positions.

4. The Hering-Mount technique [13] is a refinement of their "normal" or climatological average. "This forecast method is defined simply by averaging the past 12-hour velocity with the 'normal' speed to give the 30 hour predicted rate of movement, and the 12 hour isallobaric direction is averaged with the 'normal' direction of 52° to give the direction forecast." This technique produced two of the more accurate placements of the expected position. The 30-hour forecast from the 1830 GMT chart indicated a track 5° south of the observed course and the distance was 80 nautical miles southeast of the actual position. The track predicted from the 0630 GMT chart

[1] In the classification system devised by the meteorology staff of Eastern Air Lines [10], this storm would be typed a Category IV Cyclone, that is, "A cyclone that has been moving from the southwest quadrant and is located beneath a southwest flow aloft."

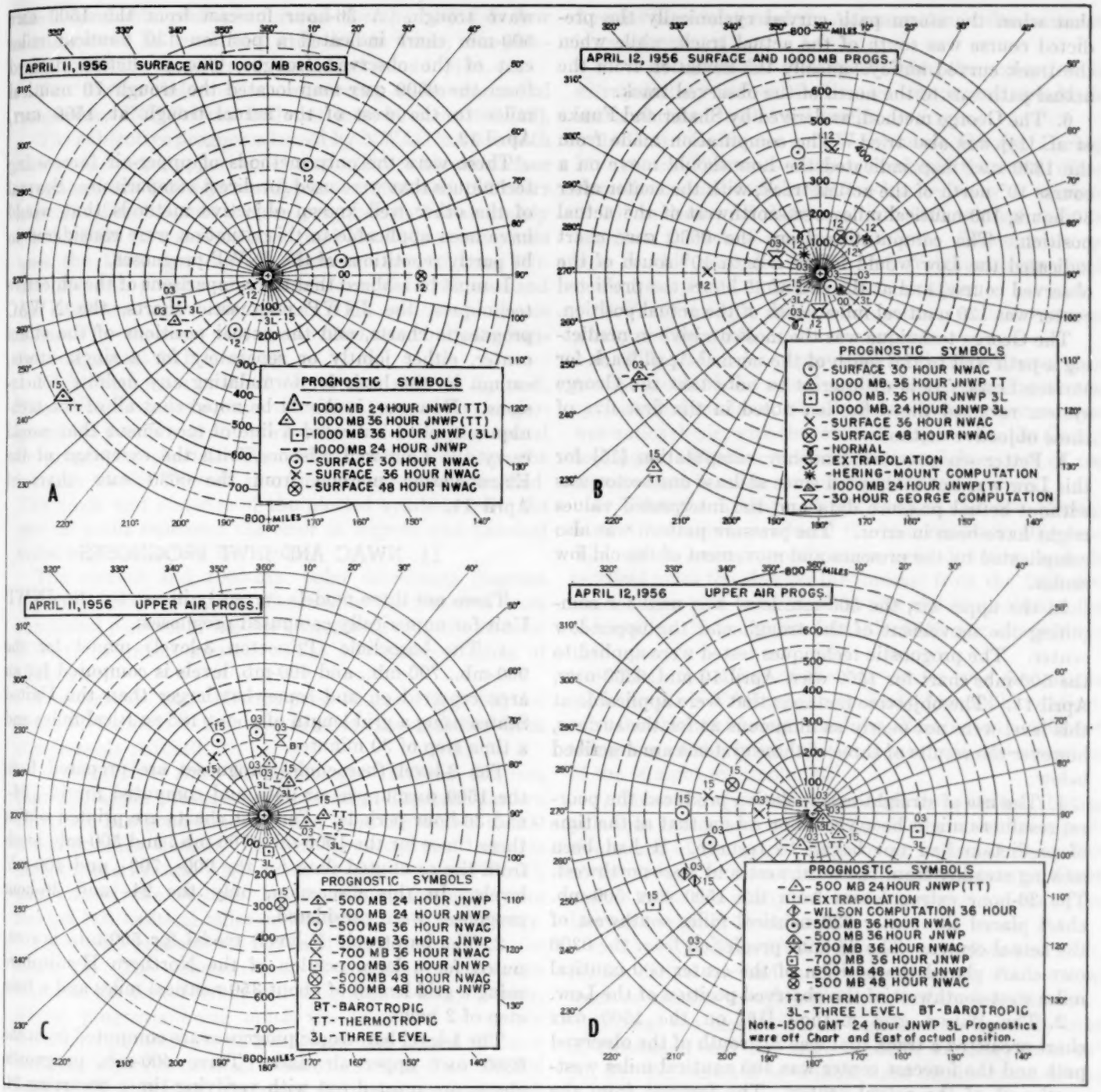
APRIL 11, 1956 SURFACE AND 1000 MB PROGS.
PROGNOSTIC SYMBOLS
1000 MB 24 HOUR JNWP (TT)
1000 MB 36 HOUR JNWP (TT)
1000 MB 36 HOUR JNWP (3L)
1000 MB 24 HOUR JNWP
SURFACE 30 HOUR NWAC
SURFACE 36 HOUR NWAC
SURFACE 48 HOUR NWAC
A
APRIL 12, 1956 SURFACE AND 1000 MB PROGS.
PROGNOSTIC SYMBOLS
SURFACE 30 HOUR NWAC
1000 MB. 36 HOUR JNWP TT
1000 MB. 36 HOUR JNWP 3L
1000 MB. 24 HOUR JNWP 3L
SURFACE 36 HOUR NWAC
SURFACE 48 HOUR NWAC
NORMAL
EXTRAPOLATION
HERING-MOUNT COMPUTATION
1000 MB 24 HOUR JNWP (TT)
30 HOUR GEORGE COMPUTATION
B
APRIL 11, 1956 UPPER AIR PROGS.
PROGNOSTIC SYMBOLS
500 MB 24 HOUR JNWP
700 MB 24 HOUR JNWP
500 MB 36 HOUR NWAC
500 MB 36 HOUR JNWP
700 MB 36 HOUR NWAC
700 MB 36 HOUR JNWP
500 MB 48 HOUR NWAC
500 MB 48 HOUR JNWP
BT-BAROTROPIC
TT-THERMOTROPIC
3L-THREE LEVEL
C
APRIL 12, 1956 UPPER AIR PROGS.
PROGNOSTIC SYMBOLS
500 MB 24 HOUR JNWP (TT)
EXTRAPOLATION
WILSON COMPUTATION 36 HOUR
500 MB 36 HOUR NWAC
500 MB 36 HOUR JNWP
700 MB 36 HOUR NWAC
700 MB 36 HOUR JNWP
500 MB 48 HOUR JNWP
500 MB 48 HOUR NWAC
TT-THERMOTROPIC
3L-THREE LEVEL BT-BAROTROPIC
Note-1500 GMT 24 hour JNWP 3L Prognostics were off Chart and East of actual position.
D

FIGURE 6.—A graphical picture of the errors in forecasts made by the various prognostic techniques tested or evaluated. The center of each graph represents the observed location of the Low. The distance and direction of deviation of the prognosis from the actual position is shown in nautical miles and degrees by the plotted positions of the different symbols. Identifying marks beside the symbols indicate prognostic techniques as follows: 3L=3 level; TT=thermotropic; BT=barotropic (all prepared by JNWP). Time of verification is next to the identifying character. (A) Surface and 1000 mb., April 11. (B) Surface and 1000 mb., April 12. (C) 700 and 500 mb., April 11. (D) 700 and 500 mb., April 12, 1956.

was 5° north of the actual path and the forecast position was 170 nautical miles southwest of the actual Low.

5. The Extrapolation method, using no anticipated curvature, produced an extremely large error on both charts. The 1830 GMT map indicated a path some 30° in error with the location of the forecast center some 700 nautical miles from the actual position. At 0630 GMT the estimated path was 20° in error and the distance from the actual center was 400 nautical miles. By this method, as in the preceding techniques, it is of interest to note

that when the storm path curved cyclonically the predicted course was south of the actual track, while when the track curved anticyclonically the deviation from the actual path was to the north of the observed track.

6. The George method, as derived by Shafer and Funke et al. [14] was also tried. The computation made from the 1830 GMT map indicated the Low should move on a course 10° north of the actual track, with the center after 30 hours, 150 nautical miles west-northwest of the actual position. The computation from the 0630 GMT chart indicated the Low would follow a path 10° south of the observed course, and at the end of 30 hours the predicted center was 120 nautical miles south of the actual position.

The George technique was the most decisive in predicting a path well to the south of the normal April track for surface Lows. It is of interest to note that the George system reversed the deflection noted in the first five of these objective methods.

A Petterssen pressure tendency computation [15] for this Low was not attempted since at least one sector was without actual pressure data and the interpreted values might have been in error. The pressure pattern was also complicated by the presence and movement of the old low center.

In the upper air, the 500-mb. level was used for computing the movement of the trough and the upper low center. The prognostic techniques tested were applied to the 500-mb. chart for 1500 GMT, April 10 and 0300 GMT, April 11. The objective methods that were applicable at this level were not nearly as numerous as for the surface, however the results of three of these systems are described below:

1. The use of straight extrapolation produced the poorest results as might be expected on a Low that at the time of prediction had not begun to recurve. It had been moving steadily from the northwest and west-northwest. The 36-hour extrapolation from the 1500 GMT 500-mb. chart placed the center 630 nautical miles southwest of the actual center. The 36-hour prediction from the 0300 GMT chart placed the position of the center 600 nautical miles west-southwest of the observed position of the Low.

2. The Wilson grid method [16] on the 1500 GMT chart predicted a track that was 22° south of the observed path and the forecast center was 460 nautical miles west-southwest of the actual center. The forecast from the 0300 GMT map indicated a track 17° south of the observed track and a center 450 nautical miles west-southwest of the actual center. The Wilson technique did not perform well for this type of situation and Wilson writes in his article, "when a surface wave development occurs ahead of the upper low, it causes the upper low to move faster than would be forecast by this method." However, it definitely indicated a track south of normal, even though the movement was slow due to such a surface wave development.

3. The Petterssen wave formula [17] produced satisfactory results in predicting the movement of the short-wave trough. A 36-hour forecast from the 1500 GMT 500-mb. chart indicated a position 130 nautical miles east of the observed trough. The prediction derived from the 0300 GMT map located the trough 70 nautical miles to the west of the actual trough at 1500 GMT, April 12.

These were the only methods of upper-air forecasting techniques that were used for direct comparison. Several of the other well known objective methods that would have been applicable to this situation were considered to be partly repetitious of the JNWP prognoses.

It must be realized that the comparisons of the objective techniques, the JNWP prognostic charts, the NWAC prognostic charts, and the actual positions of the storm center, either jointly or separately for a single storm, cannot be the basis for formulating any definite conclusions. However, it should be noted that all of the techniques applied indicated a line of movement that would carry the Low well offshore, with the exception of the Extrapolation method from the 0630 GMT chart of April 11.

11. NWAC AND JNWP PROGNOSES

There are three models currently in use by the JNWP Unit for numerically computed prognoses:

1. The baroclinic (Princeton 3-level) model for the 900-mb., 700-mb., and 400-mb. levels is computed for an area centered on and somewhat larger than the United States using a grid length of about 185 nautical miles and a time step of 30 minutes.

The 3-level (baroclinic) prognoses are prepared from the 1500 GMT upper air data and computed for 12-, 24-, and 36-hour periods. Forecast charts are printed out at these times for the 1000-mb., 700-mb., and 500-mb. levels from the computed data for the 900-, 700-, and 400-mb. levels. In this discussion, only the 24- and 36-hour prognoses were considered.

2. The barotropic (1-level) model for 500-mb. is computed for a large portion of the Northern Hemisphere using a grid length of about 350 nautical miles and a time step of 2 hours.

The 1-level barotropic prognoses are computed from the 0300 GMT upper air data. Three 500-mb. prognostic charts are printed out with verifying times occurring 24, 48, and 72 hours later.

3. The thermotropic (baroclinic 2-level) model for the 1000-mb. and 500-mb. levels is computed for approximately the same area as the barotropic model, using a grid length of 200 nautical miles and a time step of one hour.

The thermotropic prognoses are computed from the 0300 GMT upper air data and are printed out for the 1000-mb. and 500-mb. levels with verifying times of 12, 24, and 36 hours in advance. These forecasts are prepared only 4 days a week, Tuesdays through Fridays. It is pointed out that the thermotropic prognoses were initially released April 3, 1956 on an experimental basis. Therefore,

the improbable positions forecast for the 1000-mb. low centers must be considered with that in mind; new planning to reduce these errors has since been adopted.

For further information concerning these numerical prognoses, JNWP Unit Bulletins may be consulted [18].

The subjective prognoses issued by NWAC include both the surface and upper air charts. The 30-hour surface prognoses are based primarily on the 0630 and 1830 GMT charts. The 36-hour surface prognosis is based mainly on the 0030 GMT surface chart and the 48-hour prognosis uses the 1230 GMT chart. There are two 36-hour 700- and 500-mb. prognoses prepared from the 0300 GMT and the 1500 GMT upper air charts. One 48-hour prognosis is based for the most part on the 0300 GMT chart, for verification almost 60 hours later.

With these facts in mind, let us now refer to figure 6. These diagrams were prepared without regard to the geographical position of the low centers on either the actual or prognostic charts. The central point indicates the location of the Low at the time the prognosis verified. The angle and distance of the plotted symbols from the central point represent the error in degrees and nautical miles from the actual low center.

The surface and 1000-mb. polar coordinate diagram (fig. 6A) indicates a wide dispersal in the forecasts from the actual position of the low center with only the 36-hour NWAC prognosis located within 100 nautical miles of the center.

The 700-mb. and 500-mb. polar diagram (fig. 6C) for April 11 illustrates how the area of dispersal has been considerably reduced.

On the 12th of April the surface and 1000-mb. diagram (fig. 6B) again presents a rather large dispersal pattern but there is a good concentration from the center to 200 nautical miles distant. It will be noted that on this diagram the 24-hour JNWP 3-level, the 30-hour NWAC, and one of the 30-hour Hering-Mount forecasts were located 100 nautical miles or less from the actual center.

Figure 6D presents the 700- and 500-mb. prognoses for April 12. The concentration of the JNWP forecasts was near the actual center with only the 700-mb., 36-hour, 3-level prognosis being much too fast; the baratropic 48-hour, thermotropic 36-hour, and the 3-level 36-hour forecasts were 100 nautical miles or less from the observed center. The NWAC forecasts indicated a movement nearly 10 knots less than the actual speed.

12. CONCLUSION

In concluding the discussion of this case, we shall summarize some of the salient aspects of the objective prognostic techniques. In this regard we have two questions to be answered. Would any of the more widely used objective prognostic techniques have forecast a course south of the normal April track? And if any of them would have predicted a southward departure, what would have been the deviation from the actual path of this storm and by which technique or techniques would the forecast have been made? A summation of these answers is as follows:

1. That all techniques used, with the exception of extrapolation, indicated that the movement would be south of the normal April track.

2. That the Bowie and Weightman, George, Hering-Mount, and Palmer techniques furnished the actual direction of movement of the surface low center with an error of 10° or less. All distances were 200 nautical miles or less from the actual center of the Low. The only exception to this was the Bowie and Weightman prognosis made from the 1830 GMT chart of the 10th.

3. That straight extrapolation was quite erroneous when used by itself.

4. That the tendency prevailed for these prognoses to be too far south of the actual track when the curvature was cyclonic and too far north of the track when the curvature was anticyclonic, with the reverse being true for the George technique. Whether this would prevail in a test of numerous cases is not known at this time.

5. That the average of the George and the Hering-Mount techniques produced the best results in this case. The errors were approximately zero direction and 50 nautical miles too slow on the forecast from the 1830 GMT chart of the 10th and zero direction and 80 nautical miles too fast for the prognoses from the 0630 GMT chart of the 11th.

6. That the distance the low center was forecast to move by the NWAC prognostic analyst would have alleviated the threat of heavy rain from Washington northward using any of the foregoing techniques with the exception of the straight extrapolation.

7. That the upper-air techniques investigated (Extrapolation, Petterssen, and Wilson) indicated either a position south of the actual route or an eastward projection of the trough in excess of the actual movement. There was no indication of any northward movement of the upper Low or trough in these cases.

8. That all of the JNWP prognoses, surface and aloft, for the 12th either had the low centers south of the actual track or had the trough position east of the low center.

9. That the block with its high positive anomaly west of Greenland and the large negative anomaly near 43° N., 51° W., resulted in a southward displacement of the westerlies. This type block is known to deflect storms south of their normal track.

10. That the NWAC prognosis for the direction of movement of this storm was unfavorably influenced by the analysis of the 0930 GMT surface chart. From this analysis it appeared that the Low development northwest of the Gulf storm center was a break-off Low from the Gulf of Mexico cyclone and not the old Low from the Memphis region undergoing rapid eastward displacement or regeneration.

Thus it appears from this study that a movement south of the normal April track could have been anticipated and forecast. Such a prognosis would have eliminated the

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prediction of heavy rains in the States north of Virginia.

It is thought that this sentence from the writings of the French mathematician Emil Borel is appropriate as a closing statement and as a reminder to all analysts and forecasters of weather. "Neither common sense, nor calculations, can insure us against misfortune, and it will always be a meager consolation for an individual to think that the probability of misfortune was slight, when he is the one to suffer from it."

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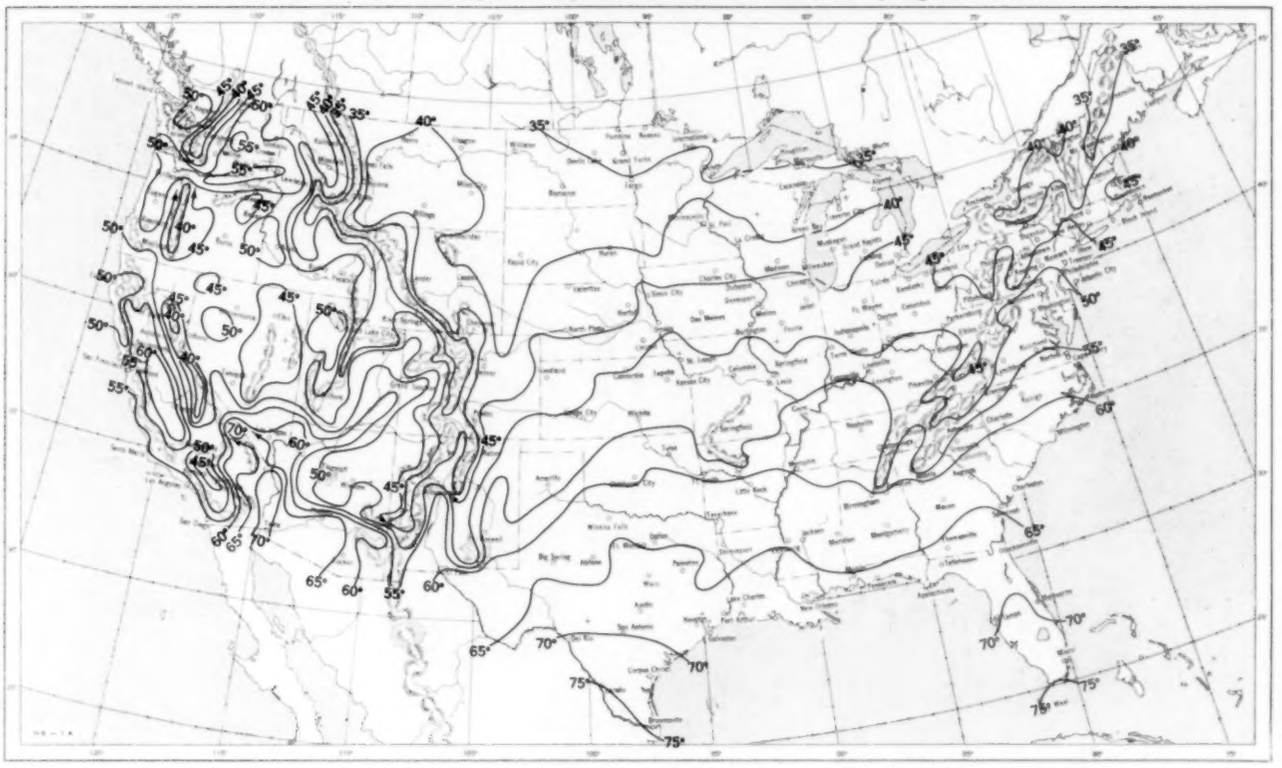
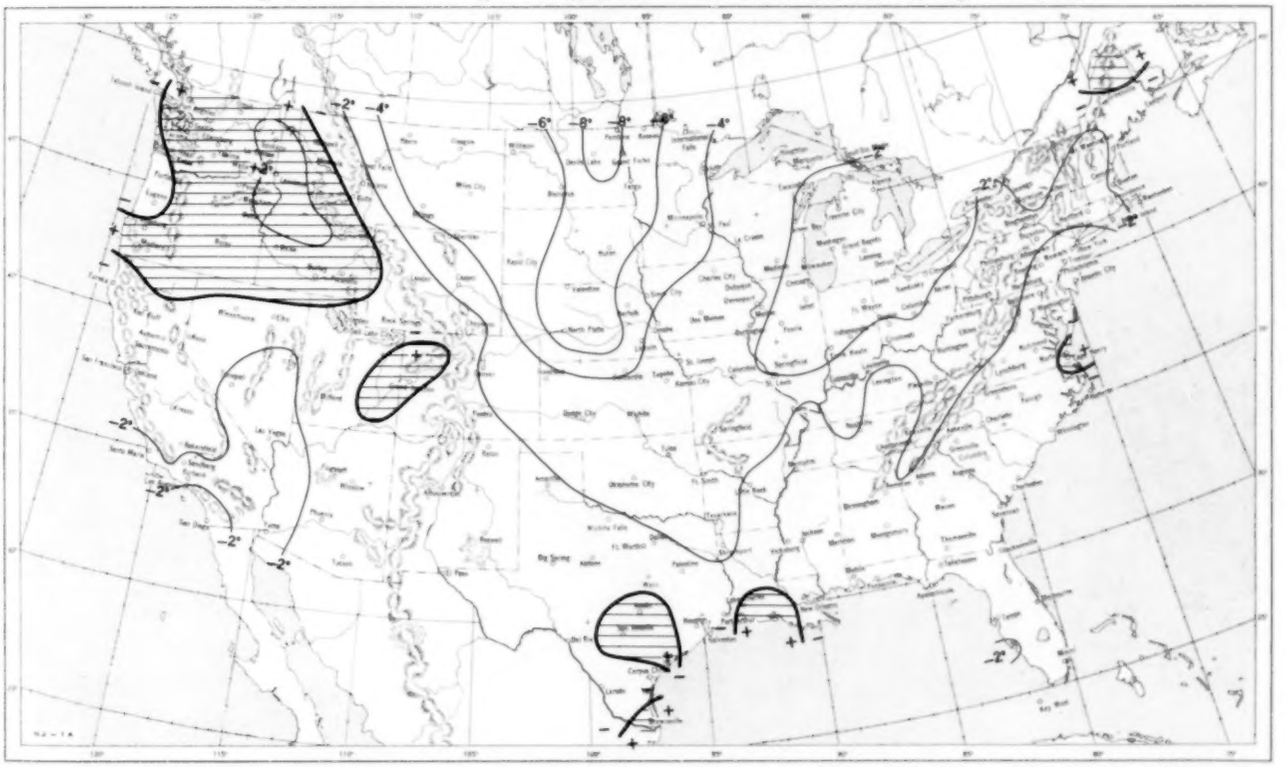
Chart I. A. Average Temperature (°F.) at Surface, April 1956.



B. Departure of Average Temperature from Normal (°F.), April 1956.



A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

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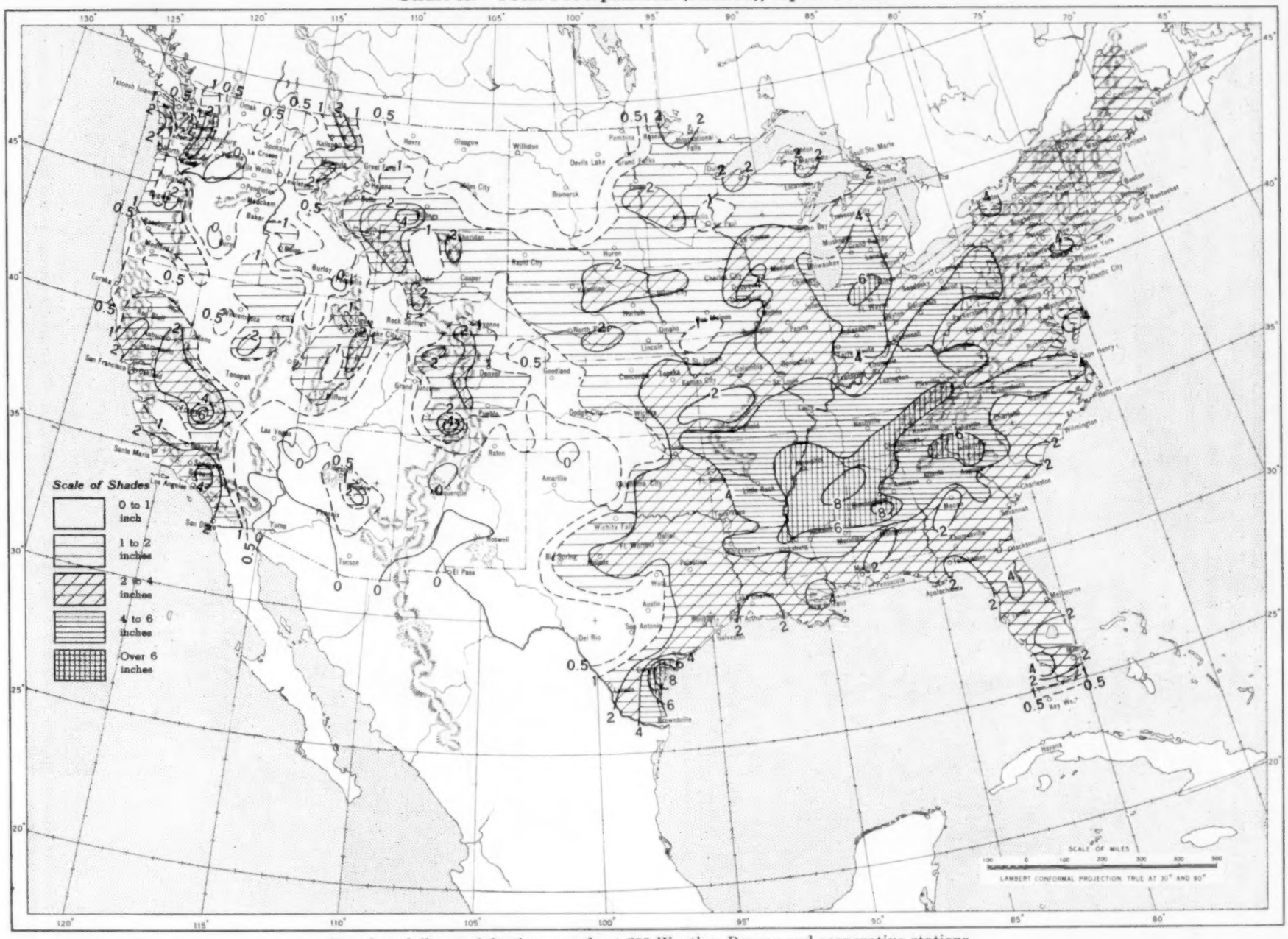
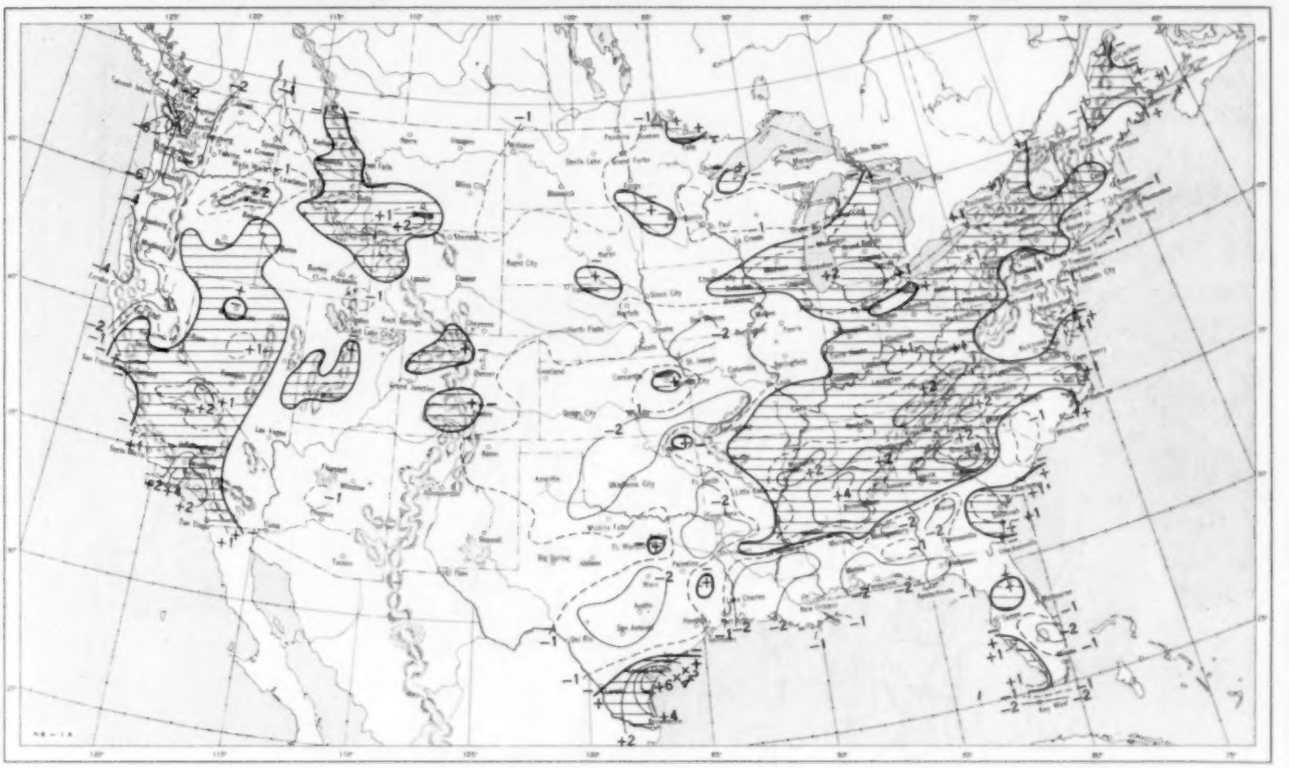
Chart II. Total Precipitation (Inches), April 1956.

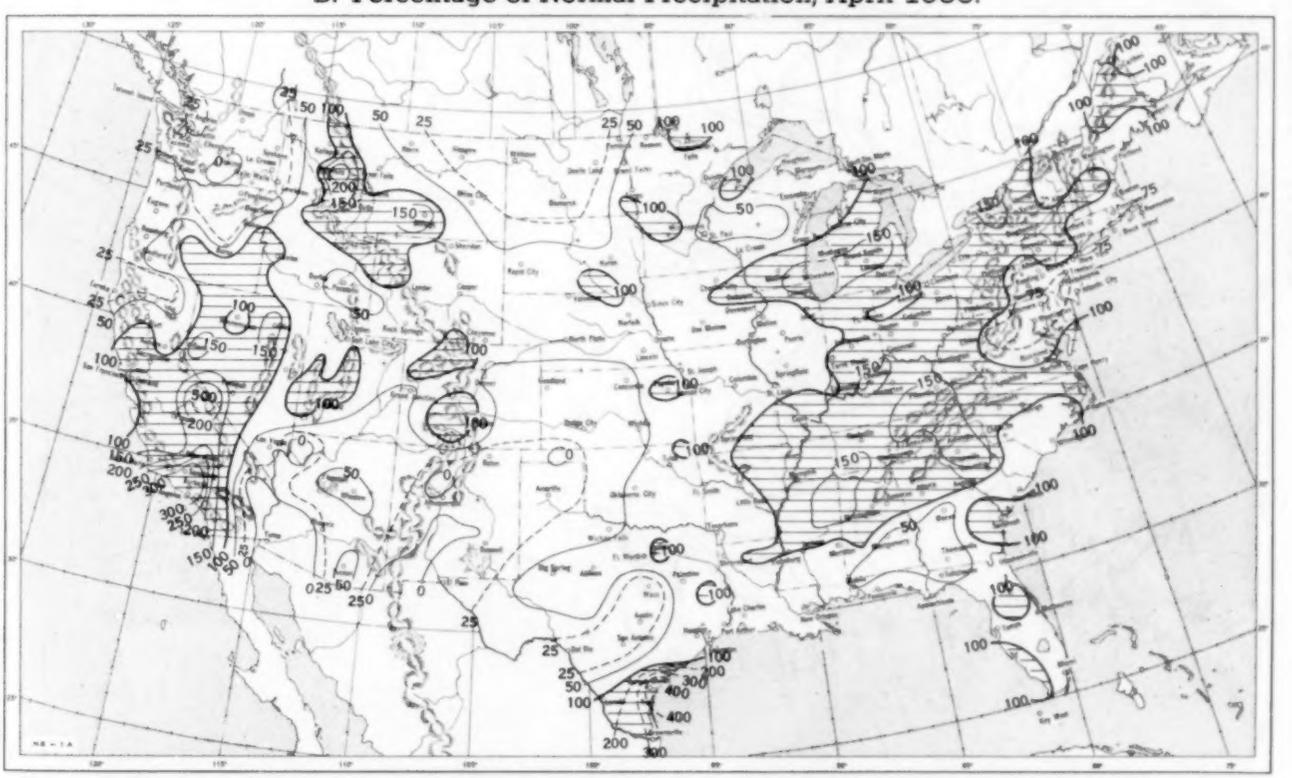

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), April 1956.



B. Percentage of Normal Precipitation, April 1956.



Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

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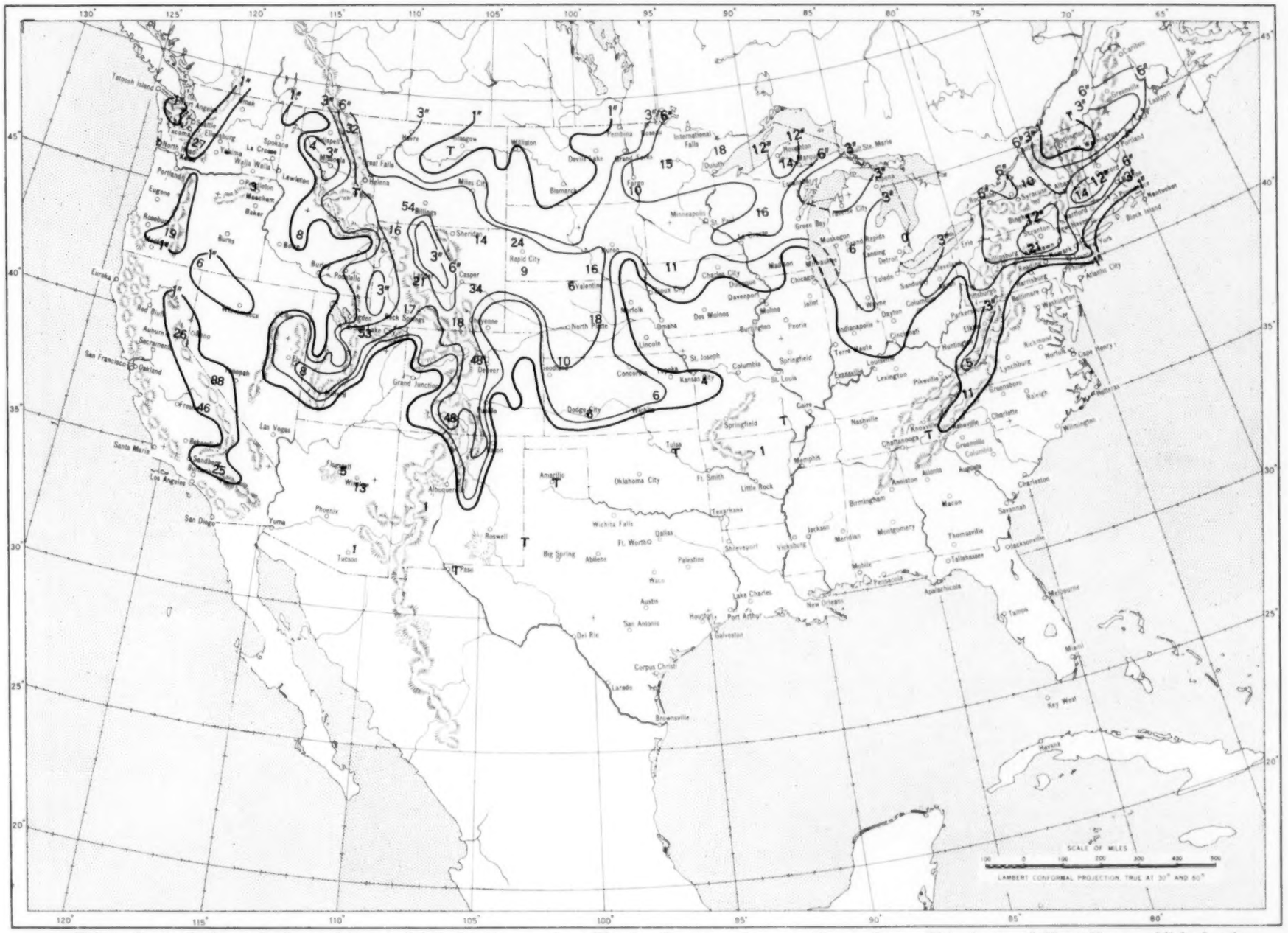
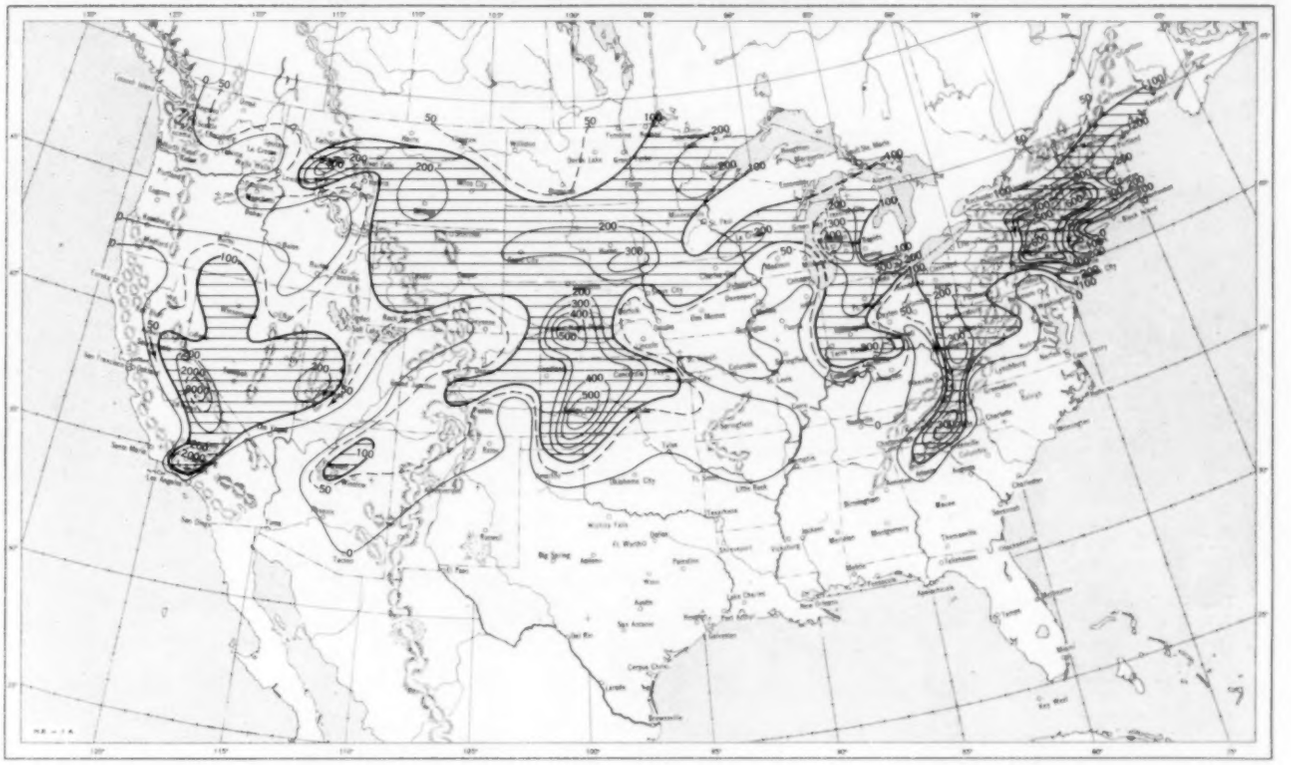
Chart IV. Total Snowfall (Inches), April 1956.



This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, April 1956.



B. Depth of Snow on Ground (Inches). 7:30 a. m. E. S. T., April 30, 1956.

A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

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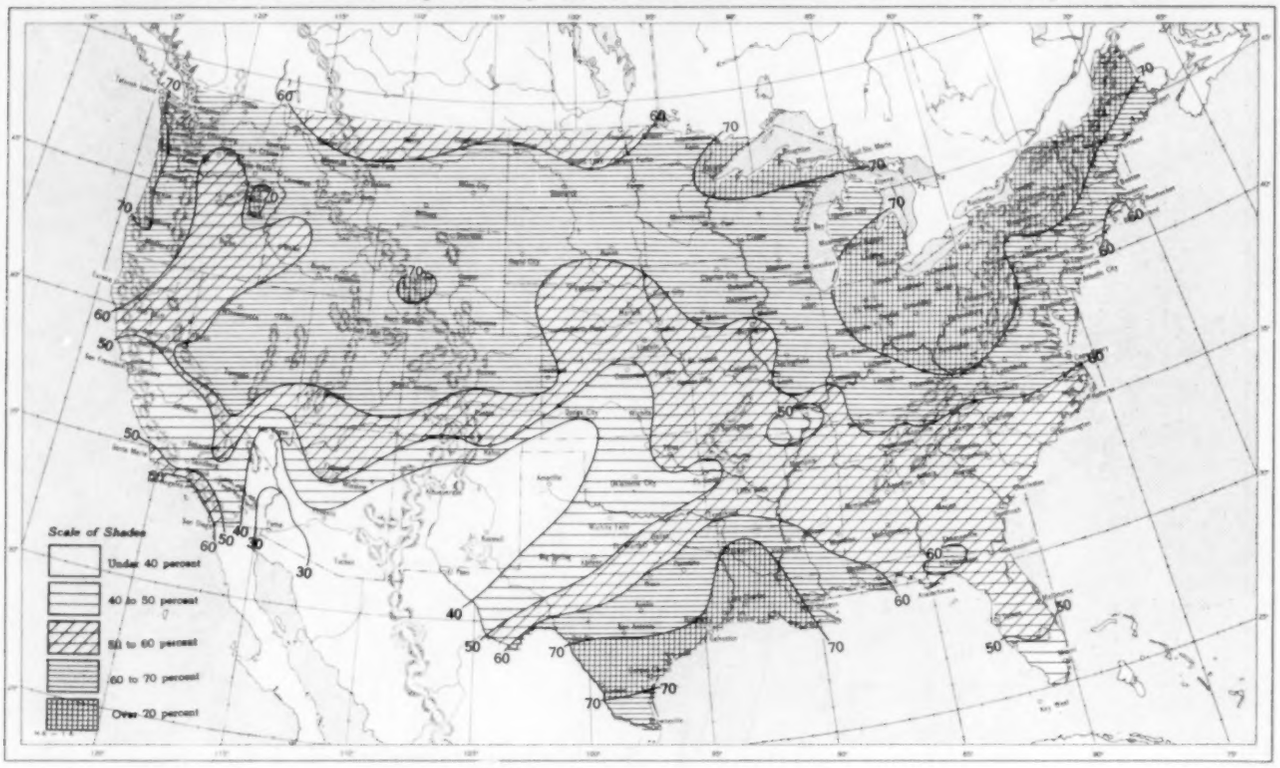
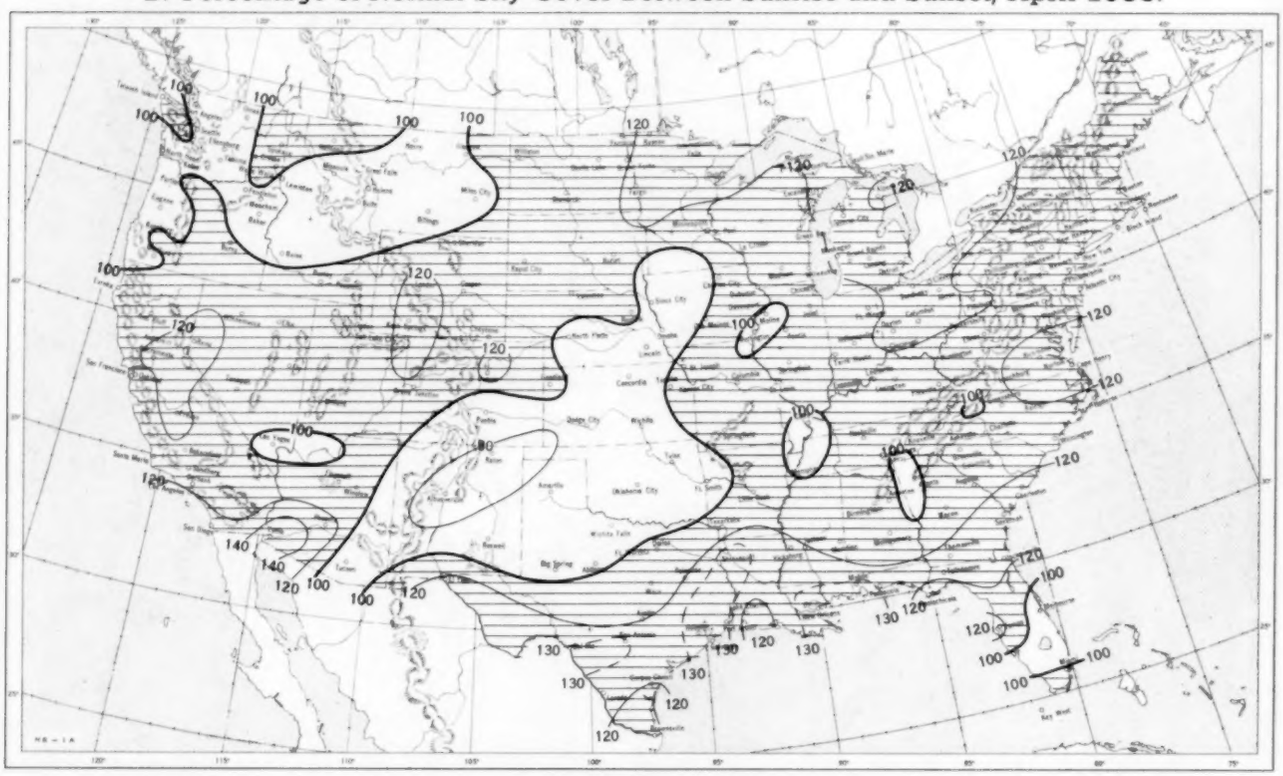
Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, April 1956.

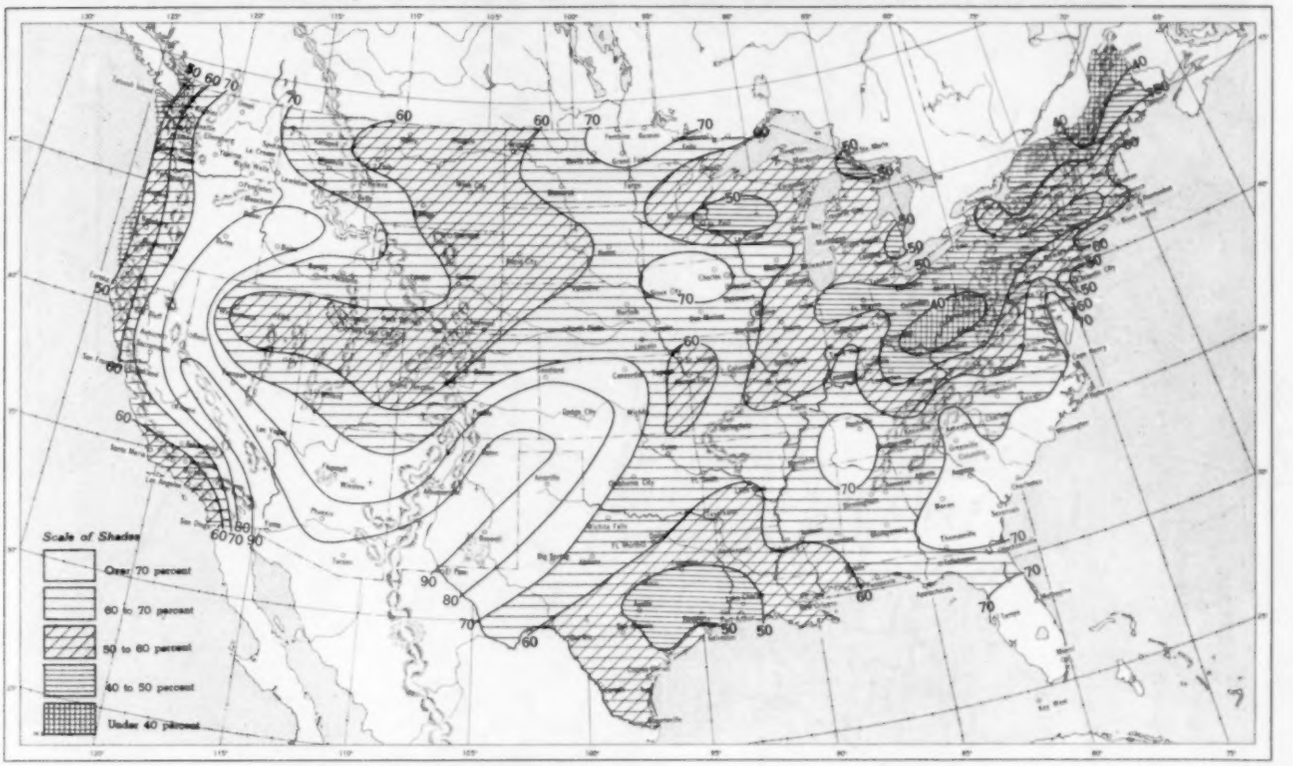


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, April 1956.

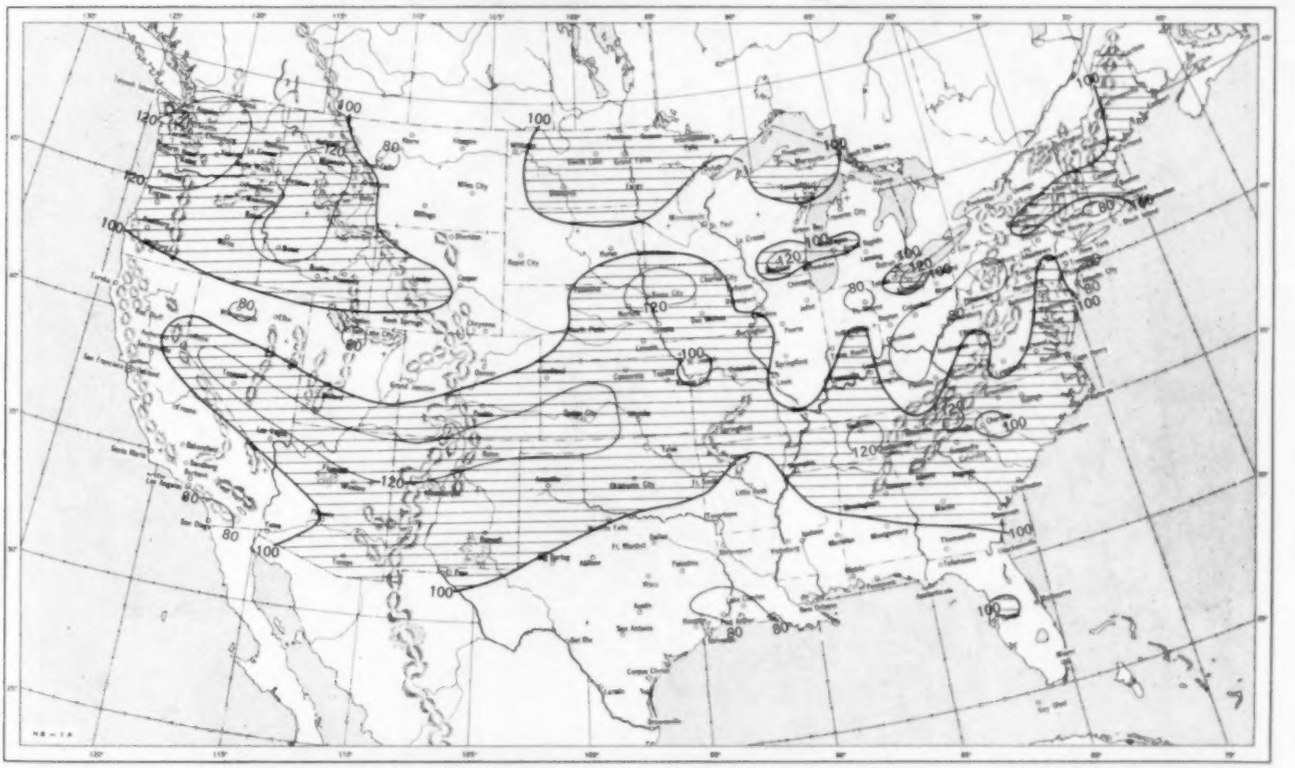


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, April 1956.



B. Percentage of Normal Sunshine, April 1956.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

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Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, April 1956. Inset: Percentage of Mean Daily Solar Radiation, April 1956. (Mean based on period 1951-55.)

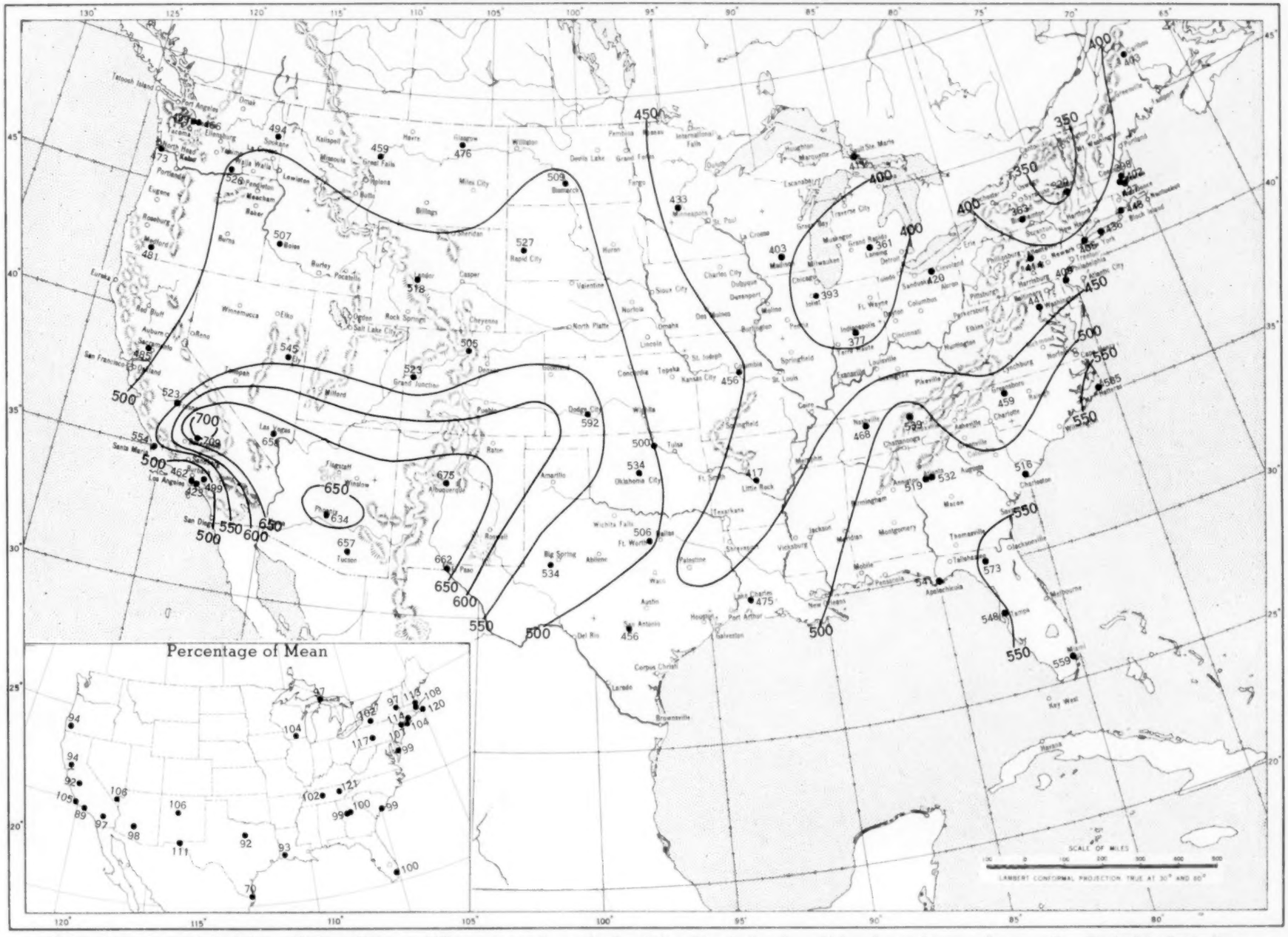
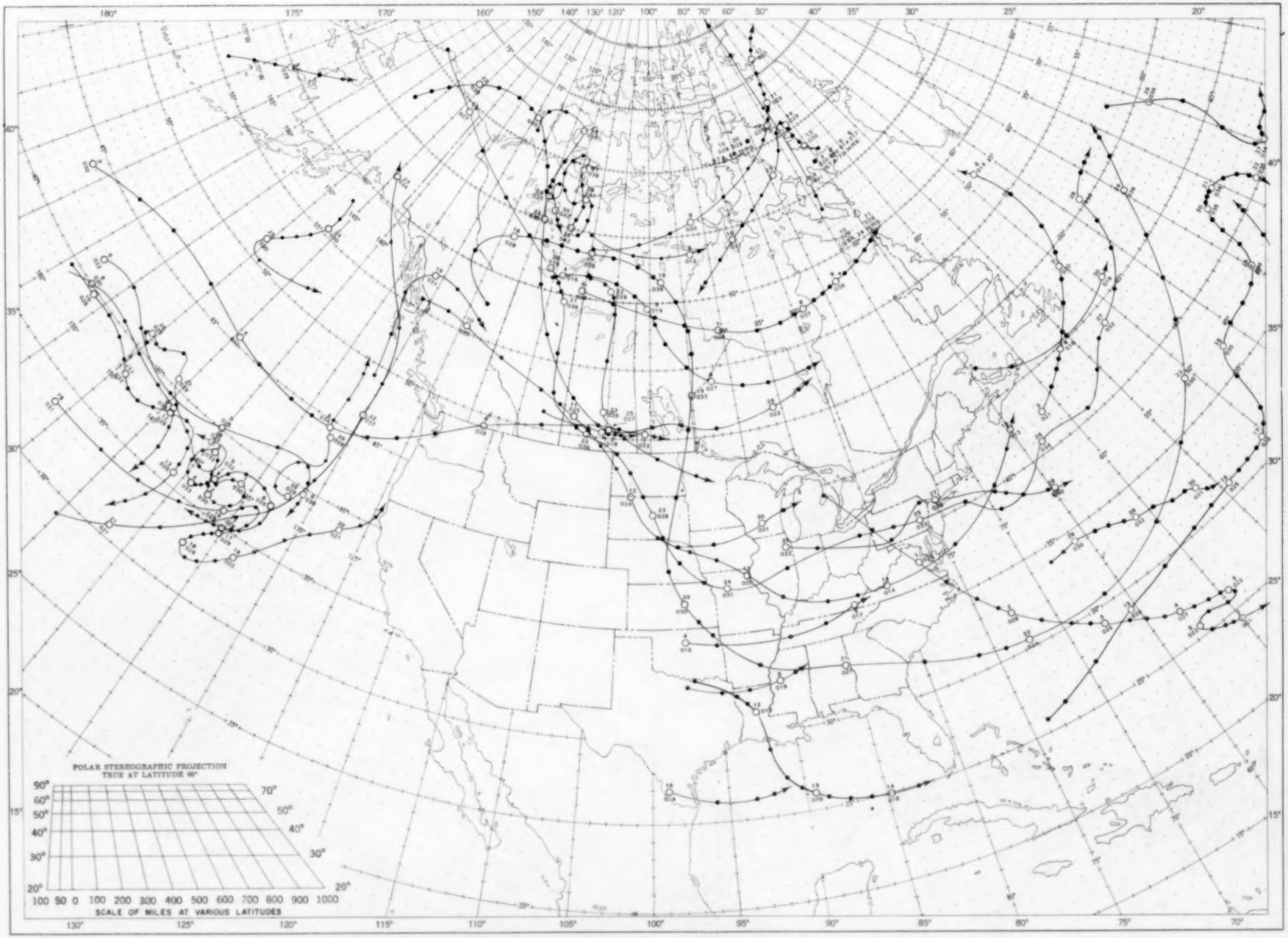


Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, April 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 90 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

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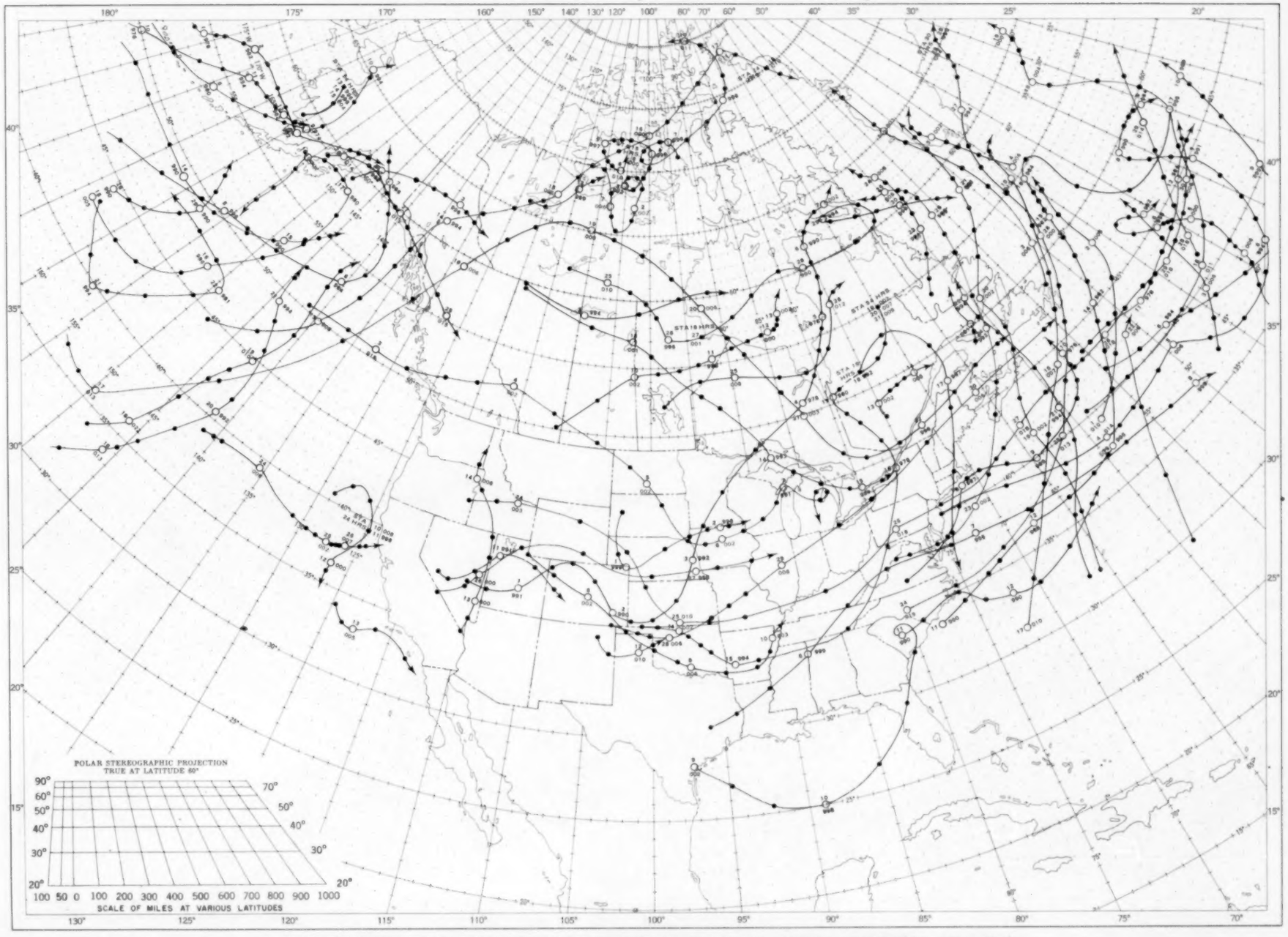
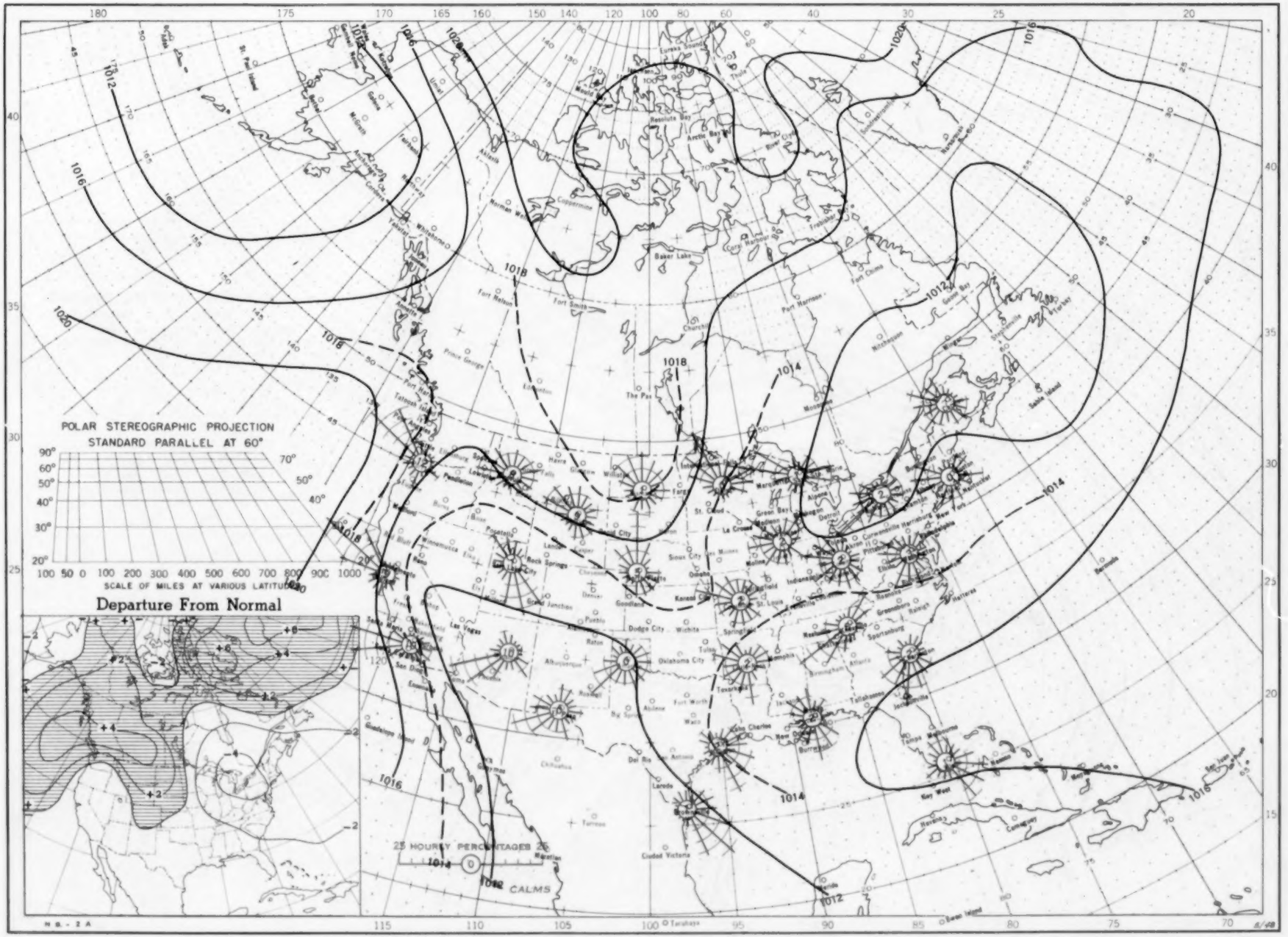
Chart X. Tracks of Centers of Cyclones at Sea Level, April 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, April 1956. Inset: Departure of Average Pressure (mb.) from Normal, April 1956.



Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

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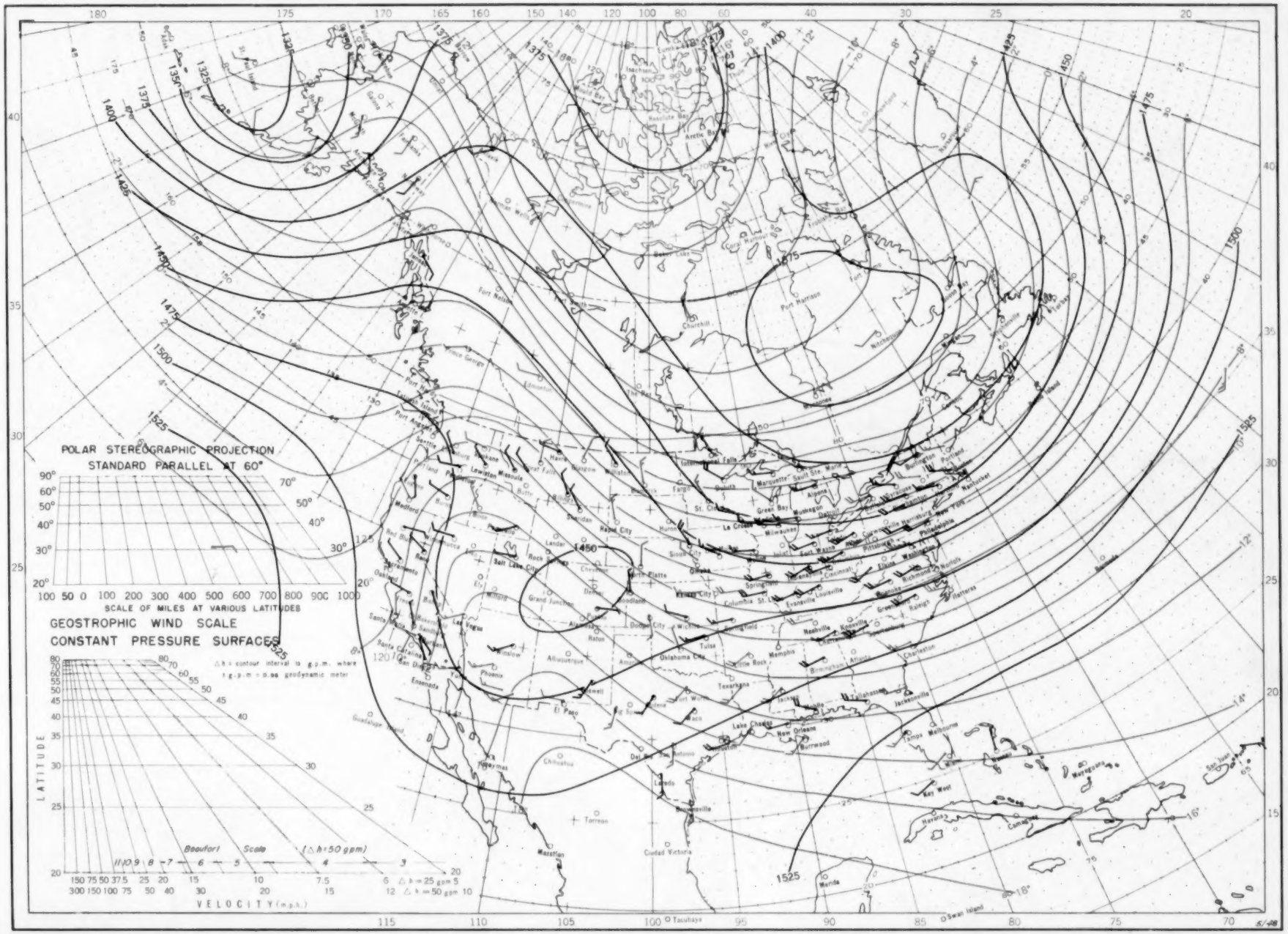
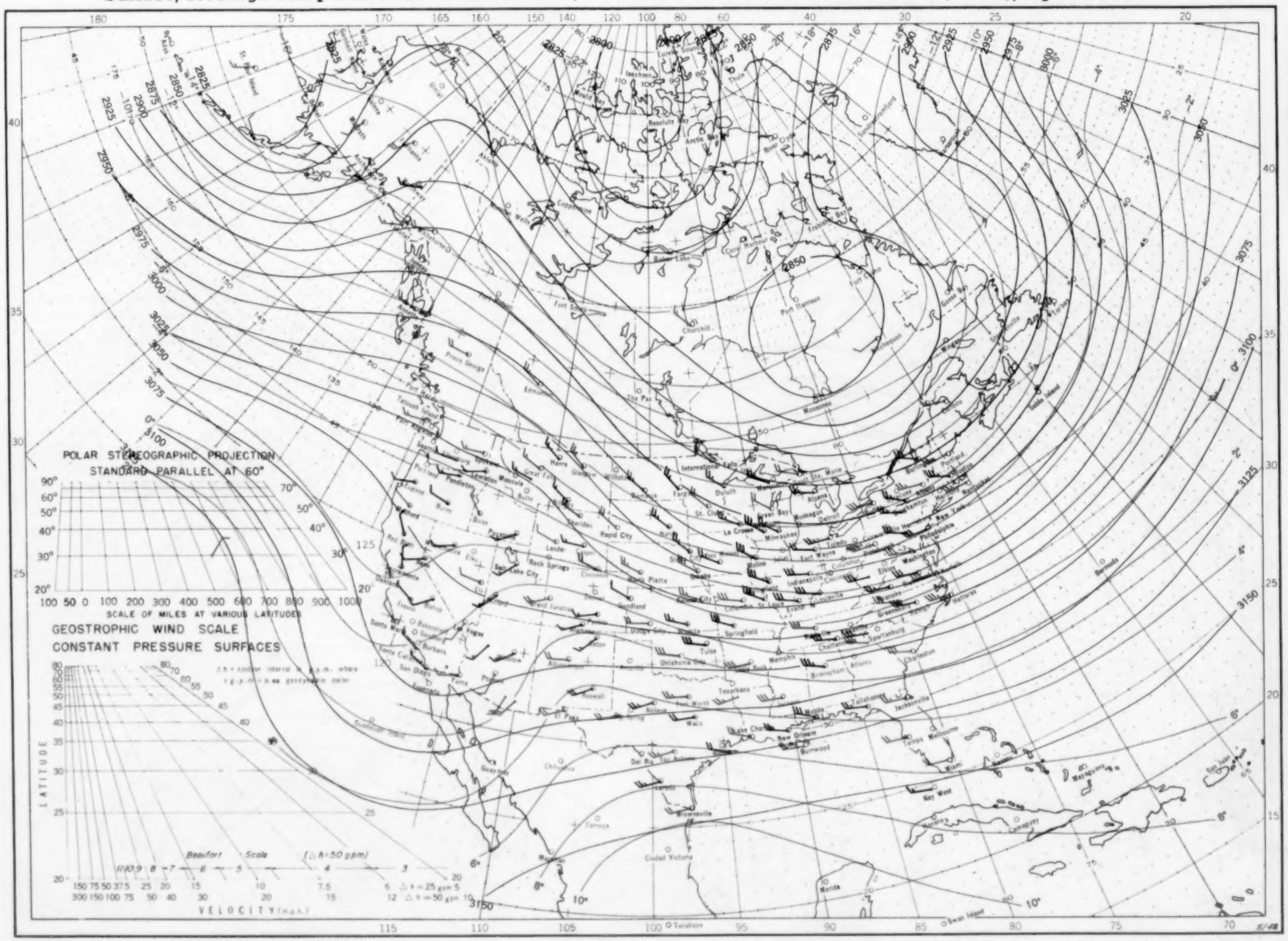
Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), April 1956.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), April 1956.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

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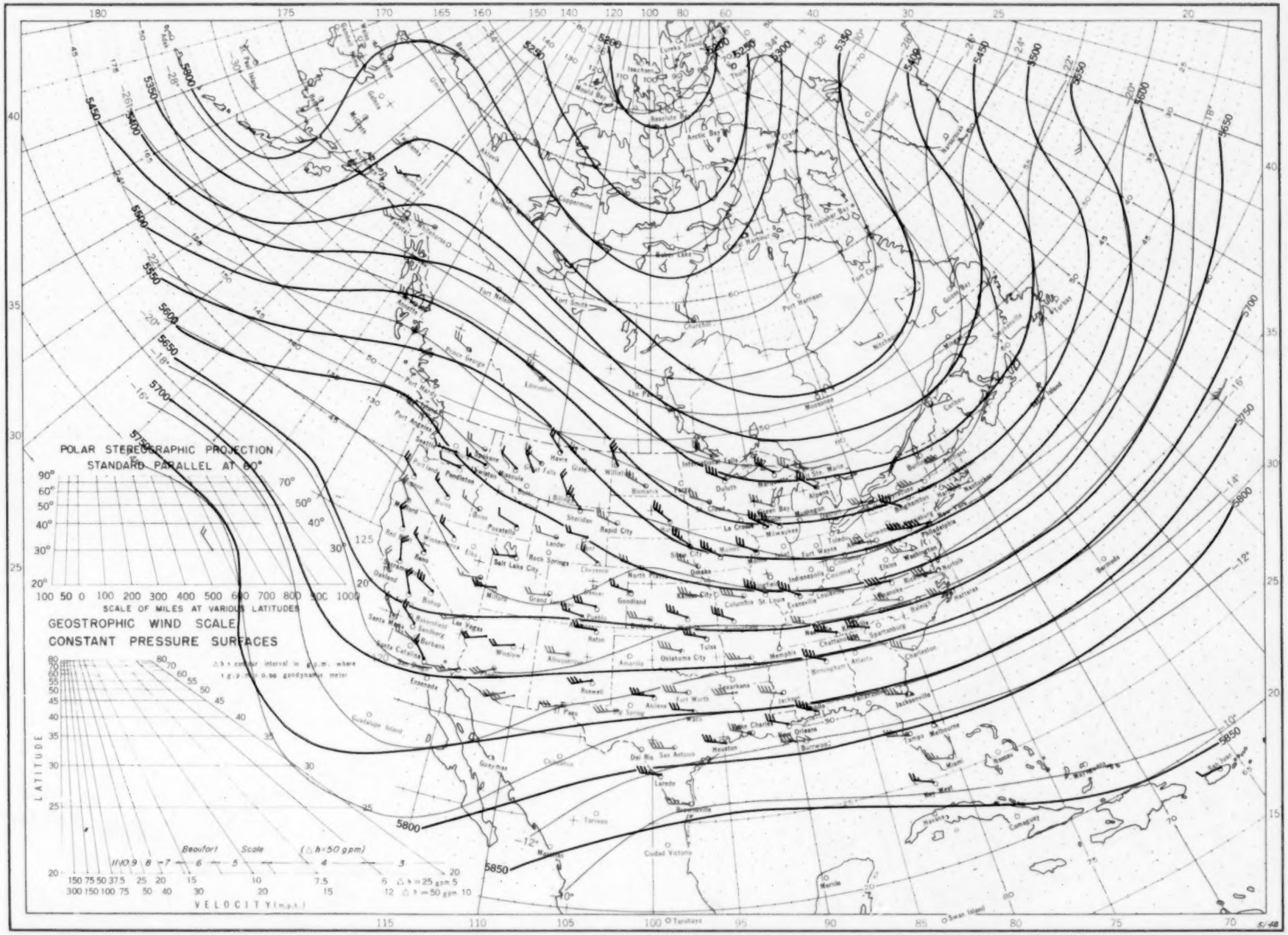
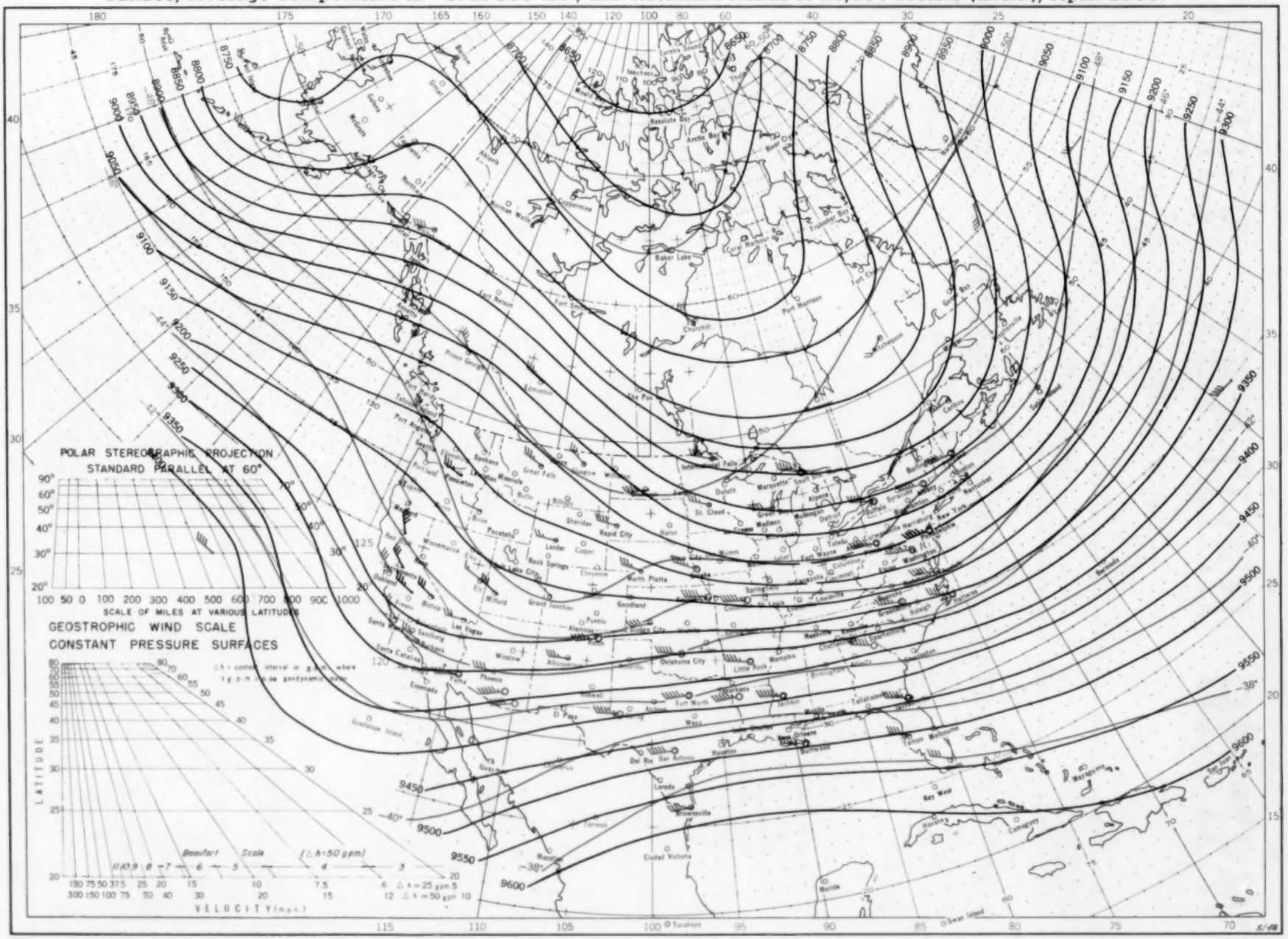
Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), April 1956.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), April 1956.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. those shown in red are based on rawins at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; Wind barbs indicate wind speed on the Beaufort scale.

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